The Development of a Manufacturing Failure Mode Avoidance Framework for Aerospace Manufacturing

James GOODLAND

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Faculty of Engineering and Informatics

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Abstract

James Goodland

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In order to remain competitive in the global market businesses are under ever increasing pressure to ramp up production rates whilst simultaneously improving cost effectiveness to allow continued profitable growth. This requirement is particularly challenging in high value manufacturing which is characterised by expensive product and manufacturing systems and relatively low production volume.

This thesis introduces a method for the design of robust and reliable manufacturing processes through the prevention of identified potential failure modes that is based on the principles of the existing Failure Mode Avoidance framework used for automotive system design.

The tools and techniques that exist in the literature are reviewed in order to understand the best practice, and subsequently a Manufacturing Failure Mode Avoidance framework is designed. This framework is demonstrated through two unique case studies conducted in a real life manufacturing environment in order to validate its appropriateness to provide robust countermeasures to failure which will allow right first time manufacture.

The outcomes of the implementations are discussed, conclusions drawn and opportunities for further research are provided.

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1 Introduction

1.1 Background

1.1.1 The Defence Industry

Due to business consolidation through mergers and acquisitions within the defence industry compounded with, and arguably catalysed by, continuing heavy reductions in worldwide defence budget spending (Deloitte 2013), the aerospace market is more competitive than ever with huge, long term make or break contracts becoming an ever increasing reality (Gabbai 2005). Contracts of this nature bring with them huge costs due to programme developments, long pay-back periods and ever greater technological complexity but provide financial advantages in terms of economies of scale and temporary security. For example, in terms of large civil aircraft production, every doubling of production reduces unit costs by around 20% (Commission of the European Communities, 1997). Additionally, investment in technological capabilities and assets is stimulated by the confidence that comes with the confirmation of new contracts improving the abilities of a business to win future orders.

This describes the scenario that is being experienced by the large, multinational aerospace Company where this research has been carried out. This organisation can boast a prestigious history of pioneering engineering accomplishments in both the civil and military markets and consequently possesses a work force with a wealth of experience and expertise in developing and applying ground-breaking technologies, which has proved pivotal in the delivery of aircraft programmes. Due to the nature of the business, details of the Company are not included in this research. This does not have any detrimental effect on this research.

Despite previous successes there are a number of current pressures that are being exerted on the Company due to the current market environment. Firstly, there is intense worldwide competition from a number of other manufacturers and distributors that produce and sell similar products, which can be illustrated by the amalgamation in the US to just a few principal contractors (MarketLine, 2011). Also, the dependency on large contracts outlined previously, brings an

additional risk associated with their loss or expiration, and with the cost of developing a bid starting in the order of millions of pounds, the need to secure and execute a contract is critical to commercial survival. Furthermore, the increasing hostility of the financial environment has made fixed price contracts ever more common. Contracts of this nature pose inherent risks as actual performance costs can be difficult to predict over the programmes duration and are liable to spiral out of control. Failure to predict and prevent technical issues and accurately estimate and control costs can have huge impacts on profitability. Finally, the economic presence that organisations of this magnitude have means that their performance regularly makes the headlines; News of poor or uncertain performance quickly spreads, with resultant damages to the Organisation's reputation being incalculable, but certainly represented through share value.

No consumer, independent of the scale or even the required urgency of procurement, can deny that price is one of the most pivotal factors in the decision making process, which becomes even more prevalent when competitors offer similar packages in terms of performance and continuing service throughout the product's life cycle (Hill, 1993). As a result, in order to remain competitive on price, suppliers need to be confident that they can maximise profits through reduction of costs, increasing shareholder value and market share. This means only one thing; minimising the costs of delivery.

However, in the last 5 years the Company has lost two contracts valued in the order of billions of pounds, which have been largely attributed to their high cost estimates. Meanwhile, secured programmes have also proved challenging encountering major technical problems which have led to years of delays and huge cost overruns. In an attempt to reduce the impact of these issues, a high level of concurrency has been adopted, which means that design, development and production of the aircraft are conducted simultaneously. Consequently, significant numbers of aircraft are being ordered and manufactured before the design is mature and the aircraft has been fully tested. Although concurrency within design has been demonstrated to be largely effective in the manufacture of quality products (Miller, 1993), conducting major production phases in parallel, rather than in a safer, linear progression, brings a high level of risk as

any problems encountered during the testing and development will require all of these early aircraft to be expensively modified, potentially rendering existing manufacturing processes and associated systems redundant. Furthermore, there is increased pressure due to demands for an increase of production rates, with aims to improve throughput by over 10 times what is currently achieved.

1.1.2 Aerospace Manufacturing

High value manufacturing is characterised by the production of high cost, low volume products. The value of the products is attributed to their superior performance capability, achieved through the application of intelligent design and manufacturing, reliant on complex and highly accurate manufacturing centres to produce components and assemblies to precision tolerances from expensive, high performance materials.

There are few better examples of high value manufacturing than in the aerospace sector, particularly in terms of military aerospace manufacture which demands the peak of the available capabilities, where performance trade-offs are not welcome considerations. Although contracts consist of relatively low order numbers, typically in the order of tens or hundreds rather than thousands of aircraft, due to the product's complexity, and the sheer number of systems, assemblies and components that they consist of, the variety of parts is still very high (Asif and Webb, 2013).

Traditionally, aerospace manufacturing has operated in a fashion typical of batch or even job production, relying on a highly skilled and experienced work force utilising accurate machining centres with a craftsmanship mentality. Historically, an aircraft consisting of thousands upon thousands of individual components would be manufactured and assembled in an almost bespoke manner. Inherently, this strategy relies heavily on continuous inspection of each single part, reflecting a 'design – build – test' approach which is not only a huge time expense but, upon the event that defects are detected, leads to a large amount of reactive activities associated with non-conformance, such as concession, rework and scrap, which are non-value adding and incur huge financial costs which consequently impact on profits. Despite technological improvements leading to a step change in the level of precision that modern

manufacturing centres are capable of, high investment is still made into part inspection due to the potentially fatal risks associated with the failure of such complex systems when used in the field. The result is a culture that has matured and plateaued, rather than evolved with the developments in part and process control technology.

1.2 Current Practice

This description is reflective of the current practice within the Company. Specific problems include;

Unacceptably high levels of out-of-specification products with associated high levels of rework and associated extra costs and delays

- Current practice does not include a process for 'closing the loop', i.e. the focus is on containment actions rather than addressing systemic root cause
- No rigorous application of process tools to assess potential failures in the manufacturing processes
- Highly complex manufacturing processes with intricate relationships between part and process parameters which consequently presents opportunity for variation to influence the process output
- Cultural issues which obstruct dialogue between different parts of the Company's operations, e.g. engineering design and manufacturing

There is a need to improve the level of parts that are right first time by moving away from reactive, containment actions and towards preventative manufacturing strategies that allow consistent delivery of quality components and assemblies, reducing the cost of poor quality and improving the profitability of manufacture.

1.2.1 Parity with Challenges Experienced in the Automotive Industry

The Company's current situation and challenges are analogous of the automotive industry during the transition from craftsmanship production to mass production and then to lean production that occurred throughout the 20th century; a need to produce quality products at higher rates and lower costs.

1.2.1.1 Mass Production

Similarly to traditional aerospace manufacturing, prior to the early 1900s automotive manufacturing comprised of highly skilled work forces developed through apprenticeships, decentralized organisations, use of general purpose machine tools to complete a variety of operations and very low production volumes (Womack, 1991). Effectively, this was the pinnacle of high value manufacturing in this era.

Henry Ford was able to secure majority market share by making automobiles affordable to the masses, designing the Model T so that it could be manufactured easily and therefore produced and sold cheaply. The key to mass production was the complete and consistent interchangability of parts, which provided simplicity in attaching them to one another (Womack, 1991), eliminating huge time costs incurred by modifying components so that they would mate effectively. The latter scenario is prevalent in manufacture at the Company. For instance, wing and fuselage skins are tailored to airframes using liquid shims and adaptive machining to ensure a precision fit (However, it is appreciated that the precision of modern aerospace components is in a different league to those of early automobiles.).

Fordist mass production worked on the premise of constant movement of the line meaning that defect parts were obliviously and continuously passed down stream. Once a defective part had become embedded in a vehicle, lengthy inspection would be required to identify it and further work required to rectify it, whilst similarly defective vehicles are continually built before the cause of the problem was found and understood.

In contrast, the development of Lean production meant that the manufacturing system was designed so that the line could be stopped immediately upon the identification of a defect; viewing the event as an opportunity for improvement rather than as problem. Instead of treating each non-conforming part as random, repairing each error and hoping it did not happen again; production would cease until a solution to prevent the problem from occurring had been devised. Initially, this method led to frequent disturbances in production but as

the organisation improved at identifying root causes and the number of errors began to drop rapidly (Womack, 1991).

This demonstrates a significant transformation in ideology from quality control to quality assurance; from part to part control to control of the process so that it yields quality parts. This attitude leads to continual improvement of the manufacturing process so that it is less susceptible to causes of faults. As a result, this system became far more effective in controlling quality than the mass production approach (Monden, 1988).

These examples have effectively demonstrated the appeal within manufacturing of producing interchangeable components consistently, whilst continuously improving the detection and correction of deviations as soon as possible during the manufacturing cycle and the benefits that these factors can yield in terms of reduction of waste as a means to enhance profitability. However, the opportunity to identify possible defects even earlier in the manufacturing time line, perhaps before the first component is even made, has greater allure that would equate to even improved prospects of efficiency.

1.2.1.2 Failure Mode Avoidance

The concept of preventing failures prior to their occurrence is central to the Failure Mode Avoidance (FMA) philosophy. FMA provides a means to prevent potential failures, or ‘failure modes’, being designed into complex automotive product systems. Through a pragmatic approach, the FMA strategy ensures that all potential failure modes are systematically identified and robust countermeasures implemented early in the design process, when the freedom for change is largest (Campean and Henshall, 2009).

Research suggests that despite huge advances in technology that allow computational modelling and rapid prototyping of automotive components and assemblies, the effectiveness of the product’s development is still constricted by late engineering changes, which appear in the form of countermeasures to design failures (Cash, 2003). Furthermore, it was discovered that 80% of the late design changes could have been avoided by using existing tools and knowledge. The FMA approach has demonstrated effectiveness through

industrial case studies (Campean et al., 2013) (Campean, Henshall and Rutter, 2013) and has been adopted by automotive manufacturers (Zhou, 2005).

1.3 Need for Research

By marrying the themes that have been explored in the section, there was a need for research to provide a solution to the challenges experienced by the Company. In essence, high global competitiveness combined with demands to increase production rates requires the Company to manufacture parts at greater cost effectiveness. Following a mass production paradigm provides an opportunity to increase rates, but at a risk of incurring unsustainable costs due to defective part production that is hard to resolve. The adoption of lean concepts and a process control approach provides an alternative, but even the initial defects and disruption is undesirable and better avoided entirely. Finally, the development of Failure Mode Avoidance within automotive manufacture demonstrates an approach to identify and prevent design failures from occurring.

An opportunity existed to adopt the Failure Mode Avoidance strategy used for automotive system design and apply it to manufacturing process design, operation and control. This strategy aids in the transition of the Company from a craftsmanship mentality, with emphasis on conformance on a part basis and a reactive approach to defects, to a process based manufacturer, allowing efforts to be focussed on process control which facilitates the reduction of cost of non-conformance whilst allowing increases in productivity.

This required the development and implementation of a structured and systematic framework similar to that used in Failure Mode Avoidance; allowing identification of the factors that influence process variability and part quality, and their management through effective manufacturing process countermeasures and controls. Based on the current situation, the following criteria were outlined for such a framework;

- Manage the complexity of aerospace manufacturing processes

- Identify and understand the interfaces, exchanges and dependencies between part and process characteristics and the process environment, identifying key sources of variation
- Systematically identify and prioritise potential process failures, their root causes and their downstream effects on the process
- Develop and deploy robust countermeasures for the avoidance of critical failures
- Validate and monitor in-process the effectiveness of the deployed countermeasures through dynamic process controls
- Document the analysis in order to 'close the loop' through lessons learnt for process knowledge reuse
- Deploy effectively within the Company's employees and culture

1.4 Aims and Objectives

The aim of this research was to develop a Manufacturing Failure Mode Avoidance (MFMA) framework that meets the criteria described above and to test its feasibility through practical case study applications.

The key objectives to achieve this aim were;

- Complete a literature review into manufacturing quality methods and how they are applied
- Develop a MFMA framework that utilises the strength of existing methods
- Trial the proposed MFMA framework in a real life environment
- Discuss the applicability of the MFMA framework based on the results of the practical case studies

1.5 Research Methodology

The method that has been used to conduct this research was as follows;

1. Carry out a critical review of current literature
2. Evaluate critically the current practice at the Company
3. Develop a MFMA framework based on the findings of the literature review and gap analysis with current processes used in the Company
4. Plan the validation of the MFMA framework through practical case studies

5. Carry out the first case study, evaluate results and refine the MFMA framework accordingly
6. Carry out a second case study with exposure to members of the organisation
7. Discuss results
8. Draw conclusions and provide recommendations for further study

This research was conducted as part of a Knowledge Transfer Partnership (KTP) with the University of Bradford and the Company, and with support from Innovate UK, who were known as the Technology Strategy Board at the beginning of this project. The Author's role was that of KTP Associate, tasked with developing and implementing the MFMA framework. This provided the opportunity for the Author to have access to the Company's facilities in order to conduct observations and case studies. Unless otherwise stated, the work demonstrated in this thesis has been conducted by the Author with combined support from staff members at the Company and University of Bradford. The original plan for the KTP project can be found in Appendix D.

1.6 Thesis outline

The structure of this thesis is as follows;

Literature review – This section provides a review of existing quality manufacturing strategies, methods and tools with a discussion of their strengths and weaknesses. Failure Mode Avoidance is examined, its philosophies and the mechanisms by which it works in order to understand how an equivalent strategy for manufacturing process control design is achieved.

Research Methodology – In this section, the current practice of the Company is discussed and compared to the findings from the Literature Review. Based on this analysis, the MFMA framework is outlined and its mechanics are described. The research objectives are described and a methodology is provided that describes how practical case studies are used to validate the MFMA framework.

Case Study 1 – This section describes the environment and aims, demonstrates the results, provides a discussion and identifies areas of improvement that result from the first case study.

Case Study 2 - This section describes the environment and aims and demonstrates the results from the second case study.

Discussion – A detailed discussion of the outcomes of the second cases study, including the strengths and weaknesses of the MFMA framework based on the two practical case study implementations. The suitability of the case studies is discussed and any advancement on the literature described.

Conclusion – This section provides a summary of the work, the conclusions that can be made and the opportunities for further study.

2 Literature Review

2.1 Quality

2.1.1 Defining Quality

The word quality is used on a daily basis, with most people having a conceptual understanding of the term, generally implying a level of value and relating it to the number of desirable features possessed by a product or service. Although this loose meaning is adequate for typical conversation, a more precise definition is required.

There are many overlapping academic interpretations of the term ‘Quality’. J. M. Juran (1974), commonly referred to as ‘The Father of Quality’, simply states that ‘Quality is fitness for use’. This succinct summary demonstrates credibility through adoption in many texts including Hoyle (1997), Montgomery (2000), Bicheno (2002) and Oakland (2003), but does not provide any insight into what qualifies a product or service as fit for use.

Crosby’s (1979) definition that ‘quality is conformance to requirements’ is consistent with Juran’s, and just as concise, but begins to add an element of engineering context by connecting it with requirements set for a product or service. This idea is harmonious with the definition provided by the British Standard Institute (BS 4778-2, 1991), that quality is ‘the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs’. However, neither of these statements provides insight into who determines the requirements of a product or service.

Ishikawa (1976) had the belief that quality begins with the customer, highlighted in the 11 points he uses to summarise his quality philosophy, of which one is ‘The first step is to know the customer requirements’ (Bicheno, 2002). Similarly, Oakland (2003) stresses the importance of managing quality by relating it to the customer and this is reflected in his brief definition that ‘Quality is meeting the requirements of the customer’ and Bodek in his foreword to *Handbook of Quality Tools*, provides an almost repetitive concept that quality ‘means delivering products and services that 1) meet the customers standards 2) meet

and fulfil customer needs and 3) meet the customer expectations' (Asaka and Ozeki, 1990).

From these definitions, it is justifiable to say that quality parts and services consist of adherence to requirements set by the customer and through extrapolation of this idea, it can be said that the product or service must add value to the customer. Whilst these definitions seem sufficient, none of them provide an insight into how quality is created by an organisation. However, Feigenbaum (1991) gives a holistic definition that quality is 'the total composite product and service characteristics of marketing, engineering, manufacture, and maintenance through which the product and service in use will meet the expectation by the customer'.

2.1.2 Quality in Manufacturing

Montgomery (2000) gives further reference to the concept of quality in manufacture, by dividing the 'fitness for use' description into two general aspects; Quality of design and quality of conformance. Through this means, he refers to quality of design as the ability of the product or service to meet the requirements desired by the customer, but attributes the quality of conformance to how well the product conforms to the specifications set by the design. The latter aspect of quality is affected primarily by the manufacturing of the product, or the delivery of the service, by factors such as the choice of the manufacturing process, the training and supervision of the workforce, the types of process controls and inspection methods employed and even the motivation of the workforce to achieve the quality required, along with multiple other influences and sources of variation (Montgomery, 2000). Oakland (2003) echoes this view, and adds that customer satisfaction must be designed into the production system. Consequently, both Montgomery (2000) and Oakland (2003) prefer a modern definition of quality; Quality is inversely proportional to variability.

As a result, with respect to the manufacturing industry, the duty of the quality department is to reduce the level of variation within the manufacture of their products. Taguchi (1993) provides a very succinct definition of quality engineering; the purpose of quality engineering is to conduct the research necessary to develop robust technologies and methods that increase the

competitiveness of new products by reducing their cost and improving their quality; this enables the manufacturing enterprise to survive in the highly competitive global market.

J. M. Juran (1998) provides a definition of quality in terms of two critical aspects;

1. Quality means those features of products which meet the customers' needs and thereby provide customer satisfaction
2. Quality means freedom from deficiencies – freedom from errors that require rework or that result in field failures, customer dissatisfaction, customer claims and so on

What is interesting about the two aspects of quality that Juran describes is that the first relates to the income of the producer, as higher quality typically costs more to the consumer, whereas the second aspect is related to the cost to the producer, where higher quality costs less.

2.1.2.1 Quality Standards

The International Organisation for Standardisation (ISO) has developed a series of standards for quality systems, since their foundation in 1946. The current version of the standard is known as the ISO9000 series, which is a generic standard that is applicable to any type of organisation, and is typically used to demonstrate a supplier's ability to control its processes, and produce quality products and services (Montgomery, 2000).

Montgomery (2000) identifies some problems with the ISO standard, stating that extensive effort is required to bring documentation in line with the standard, and therefore the focus is misplaced on paperwork rather than actual improvement action and that this phenomenon is exacerbated by Auditors who concentrate on the book keeping elements of the standards. He concludes that organisations would be better off developing their own appropriate quality systems and variability reduction efforts, which would be a more efficient use of time and money.

Incidentally, several industries have produced their own industry–specific standards. Examples include the QS 9000 for the automotive industry, AS 9100 for the aerospace industry and TL 9000 for the telecommunications industry.

2.1.2.1.1 QS 9000

The aim of the QS 9000 is the development of fundamental quality systems that provide for continuous improvement, emphasizing defect prevention and the reduction of variation and waste in the supply chain (Chrysler, Ford and General Motors, 1998).

The most relevant aspect of the QS 9000, in terms of tools that support a predictive process driven manufacturing engineering production approach, is the Advanced Product Quality Planning manual which provides guidelines designed to produce a product quality plan which will support the development of a product or service that will satisfy the customer (Chrysler, Ford and General Motors, 1995).

2.1.2.2 Advanced Process Quality Planning

The Advanced Quality planning and Control Plan reference manual was released by Chrysler, Ford and General Motors in 1994. The purpose of the manual is to communicate to internal and external suppliers, and to their subcontractors, the product quality planning and control plan guidelines, developed jointly by the three automotive companies, and to outline a structured method of defining and establishing the steps necessary to ensure that a product satisfies the customer (Thisse, 1998).

The manual introduces and focuses on the five phases of quality planning and illustrates appropriate activities at each of these phases (Thisse, 1998):

1. **Planning and defining the program** – How to determine customer needs and expectations in order to plan and define a quality program. E.g. Voice of the customer, design goals, preliminary process flow chart.
2. **Product design and development** – Developing the design of a product or service and ensuring that it is feasible and will meet the customer's

expectations. E.g. Design FMEA, Engineering drawings and specifications.

3. **Process design and development** – Developing a manufacturing system and related control plans to achieve quality products. E.g. Process FMEA, process flow chart, Characteristic Matrix, measurement system analysis plan**.**
4. **Product and process validation** – Validation of the manufacturing process through evaluation of the product trial run**.** Assessment of process capability and correction of any issues prior to full scale production. E.g. product trial run, preliminary Process Capability Study, production control plan.
5. **Feedback, assessment, and corrective action** - Evaluation of all special and common cause variations and the effectiveness of the quality planning effort itself.

Every organisation will be conducting some aspects of APQP, as virtually every program or activity has some planning associated with it. However, sometimes these efforts may not be recognised as such, and in smaller organisations the majority of the planning may be done informally (Thisse, 1998). Thisse (1998) emphasises that APQP is not a complex, added activity or 'one more thing to do'. Rather, it should involve awareness that employees have developed their roles in the planning process and understand how those roles fit into the overall plan.

2.1.2.3 Process Control Plans

Process Control Plans are a major output of the quality planning process and are the basis of the supplier's process control methodology (Thisse, 1998). The purpose of the Process Control Plan is to ensure that all process outputs will be in a state of control by providing process monitoring and control methods to control product and process characteristics (Hoyle, 1997). A Process Control Plan is a written description of a system for controlling parts and processes (Chrysler, Ford and General Motors, 1995) and is typically formatted as a table, as shown in Figure 2-1. It operates as an expansion of the current control column of the FMEA.

Process Step / Function	Machine, Device, Jig, Tools for Mfg.	Characteristics		Methods					Reaction Plan
		Product	Process	Product/ Process Specification/ Tolerance	Evaluation/ Measurement Technique	Sample		Control Method	
						Size	Frequency		

Figure 2-1 A typical Process Control Plan

Not only is the Process Control Plan an effective summary of the special characteristics affected by the process, but it indicates whether the control strategy is prevention or detection orientated. A good Process Control Plan should reduce process tampering, provide a means for implementation of process improvement activities, describe training needs for standard operating procedures and document maintenance schedule requirements (Breyfogle, 1999).

Ultimately, the control plan should remain a ‘living document’ that reflects the current methods of control, and measurement systems used. Therefore, it should be updated as these methods and systems are evaluated and improved (Chrysler, Ford and General Motors, 1995).

2.2 Key Process Terminology

2.2.1 Reliability and Robustness

Much like the term quality, ‘Reliability’ is a word that is frequently used, and although a conversational understanding is shared, a textbook definition is required. Drummer and Winton (1986) define reliability as the characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated operating period. Clausing and Frey (2005) similarly define reliability as the proper functioning of the system under the full range of conditions experienced in the field, but go on to state that it requires two critical conditions;

1. Mistake avoidance
2. Robustness

Clausing and Frey (2005), further explain that by ‘mistake’ they refer to the array of design decisions and manufacturing operations that may result in a failure mode and by ‘robustness’ they refer to the ability of a system to function under the full range of conditions that may be experienced in the field. They go on to differentiate the challenges of developing a system in controlled, laboratory conditions and the broad set of real world environmental and operating conditions.

2.2.2 Critical Product Characteristic

Glodek et al. (2006) defines a critical product characteristic as a quantifiable property of an intermediate or final product that is considered critical for ensuring the final product quality. Such properties include dimensions, tolerances, finishes or assemblies which must be within a predetermined range.

2.2.3 Critical Process Characteristic

A critical process characteristic is a process input, be it intentional or otherwise, that, when varied beyond a limited range, has a direct and significant influence on a critical product characteristic (Glodek et al., 2006). Failure to stay within the limited range leads to a high likelihood of product failure.

2.2.4 Noise Factors

Variation in a product or a process is due to a variety of causes, known as noise factors (Phadke, 1989). Noise factors disrupt the ideal functioning of a product or process, and cause undesirable outputs, known as ‘error states’ (Ford Design Institute, 2004). These are parameters classified as either difficult or impossible for the process or product designer to control, or overly expensive to control. They are also referred to as sources of variation. Phadke (1989) describes three categories of noise factors for manufacturing processes;

1. **External to the process** - in relation to the environment in which the process is carried out and the load offered to the process e.g. ambient temperature or variation in raw materials
2. **Process nonuniformity** - variation in units that are processed in batches
3. **Process drift** - due to deterioration of the process over time. As a result of tool wear for example

2.2.5 Control Factors

These are parameters that can be specified freely by the designer (Phadke, 1989), i.e. they can easily be controlled or altered in order to affect the output of process. For instance, drilling speed.

2.3 Lean

2.3.1 Defining Lean

The idea of ‘lean thinking’ was first introduced by Womack, Jones and Roos (1990) to encapsulate the overriding philosophy behind the working practices of the Japanese vehicle manufacturers and the development of the Toyota Production System. Since then the term ‘Lean’ has become convoluted (Stone, 2012) to the point where Hallam (2003) identifies that it has been used ‘to refer to four aspects of the manufacturing firm, namely the operating philosophy, the tools, the activities and the state of the manufacturer’.

Stone (2012) simply describes the lean thinking paradigm as the differentiation between waste and value. ReVelle (2001) supports this definition, but involves the concept of the customer, basing Lean on the principle of eliminating waste and therefore adding value to the customer. This idea is consistent with Womack and Jones (1997) and their description that ‘Lean provides a way to do more and more with less, while coming closer and closer to providing customers with exactly what they want’. Borris (2012) concurs but provides clear distinction that value must be ‘defined from the perspective of the customer, not the manufacturer, but both parties gain from its application’. Rother and Shook (1999) make the association between Lean and a business’ processes in their definition that ‘Lean thinking in action is the continuous identification and elimination of waste from an organisation’s processes, leaving only value added activities.’

From these definitions the following points can be concluded;

- Lean concepts are dependent on the reduction of waste
- Value is defined by the customer and can be specified

- Both waste and value are created by the organisation
- The Lean journey is continuous and there is always room for improvements

2.3.2 Lean Principles

Womack and Jones (1997) identify five key principles in adopting the Lean philosophy;

1. **Specify value** – Define value precisely from the perspective of the end customer in terms of the specific product with specific capabilities offered at a specific time.
2. **Value Stream** – Identify the entire value stream for each product and eliminate waste.
3. **Flow** – Make the remaining, value adding steps flow.
4. **Pull** – Design and provide what the customer wants only when the customer wants it.
5. **Perfection** – Strive for perfection continually by removing successive layers of waste as they are uncovered. Also to referred to as 'Continuous Improvement'.

2.3.3 Waste

Waste is defined by Womack and Jones (1997) as any activity which absorbs resources but creates no value. However, Melton (2005) suggests that sometimes waste does not add value to the customer but is a necessary part of the process and adds value to the company and thus cannot be eliminated, e.g. financial controls or research and development. In this respect, there is a case to say that not all value is directly experienced by the customer. Bicheno (2002) confronts this discussion by classifying activities as either value adding, non-value adding, and non-value adding but temporarily necessary. The last two are considered as waste, but value adding activities may either be to do with the present or the future.

Waste is recognised to occur in seven forms, known as the 'seven deadly wastes'. First identified by Ohno (1998) and reported by Womack and Jones (1997), they are as follows;

1. **Transportation** – The unnecessary motion of movement of materials contributes towards non-value added time to the process and provides an opportunity for handling damage.
2. **Inventory** – The entire inventory that is not directly required to fulfil customer orders. This requires handling and space and can require extra processing.
3. **Movement** – The extra steps taken by employees and equipment as a result of inefficient layout, defects or excess inventory.
4. **Waiting** – Periods of inactivity in a downstream process because an upstream activity has not delivered on time, possibly as a result of bottlenecking or machine breakdown.
5. **Over Production** - When operations continue after they should have stopped resulting in excess products and increased inventory.
6. **Over Processing** – Additional work such as rework, handling, reprocessing or storage as a result of defects, over production or excess inventory.
7. **Defects** – Finished goods that do not conform to the specification or customer's expectation, thus causing scrap and rework if detected or customer dissatisfaction if not.

Various authors have extended Ohno's original list. Bicheno (2002) states that Womack and Jones suggest an additional waste associated with making the wrong product correctly. This relates to their first principle of lean thinking, 'Value', and that it "begins with the ultimate customer". Today this is also the starting point of ISO 9001:2000 (Bicheno, 2002). Hicks (2007) also credits Womack and Jones with identifying a separate 'eighth' category, regarding the underutilisation of people and their ideas (Bicheno (2002) also identifies this waste but attributes it to Ohno). Hicks (2007), however, does not recognise this waste in his research stating that it is arguably inherent in the original seven wastes. Furthermore, Koskela (2004) argues that starting processing before all of the materials for production have arrived, which he dubs 'making do', should be added to the list.

The seven wastes are productivity rather than quality related, but these two are closely linked. Improved productivity leads to leaner operations which make quality issues more visible and improved quality leads to improved productivity by removing wasteful practices such as rework, extra inspection and the activities associated with completing operations for a second time (Bicheno, 2002). Shingo (1989) summarises this in his reflection that “In the past the typical approach to process improvement was to ‘improve the waste’. Instead, fundamental improvements must be made because they eliminate the waste itself and thus the need to ‘improve’ it”.

2.3.4 Lean Tools

A variety of tools and techniques including Kaizen, Kanban, Single Minute Exchange of Dies (SMED), 5S, Total Productive Maintenance (TPM), Value Stream Mapping (VSM), Total Quality Management (TQM) and many more support the lean transformation in order to remove waste, variability and overburden and deliver improvement in specific areas (Neha et al, 2013). Lean transformations employ a variety of techniques and tools but it is the fundamental understanding of waste and its removal that is critical to a successful adoption of lean (Hicks, 2007).

2.3.5 Application of Lean

The concept of Lean is validated by its diverse and popular uptake across a variety of industries. Although the ideas and techniques were developed in manufacturing, they have spread into a whole host of other business applications. The Lean Enterprise Research Centre (LERC) (2007) provides an insight into the opportunities that are available in manufacturing alone, stating that for most production operations only 5% of activities add value, 35% are necessary non-value activities and 60% add no value at all.

Within the automotive industry, the Toyota Production System (Monden, 1998) (Shingo, 1986) provides a comprehensive example. Crute et al., (2003) provide an insight into the applications of Lean in the aerospace industry, comparing the challenges experienced by two different sites of a third tier aerospace company pursuing Lean practices as a result of pressures from their customers within the industry. Furthermore, Dudley (2005) describes studies of the implementation of

Lean in a medium sized aerospace manufacturer and, in terms of large manufacturers, Lu (2002) and Chang, Huang and Torng, (2013) refer to the adoption of lean practices within Boeing during the introduction of a moving assembly line. Within military aerospace manufacture, Lockheed Martin have applied Lean techniques to the manufacture of F-16, F-22 and C-130J (Crute et al., 2003) (Chang, Huang and Torng, 2013). Aside from the aerospace and automotive industries Maia, Alves and Leao (2013) have conducted case studies into textile and clothing manufacture and Pheng and Fang (2005) describe applications in the construction industry. Outside of manufacturing altogether, Hicks (2007) investigates the application of Lean towards information management.

2.3.6 Shortcomings of Lean

Despite such widespread use and familiarity, the literature identifies a number of potential issues associated with the Lean approach. Although the principles and tools associated with lean thinking may appear to be easy to apply they present huge challenges associated with change, with cultural change being the hardest to implement for any business that truly intends to become lean (Melton, 2005). Further to this point, Seddon and Caulkin (2007) state that companies that use only the Lean tools but fail to embrace the underlying philosophy are unlikely to gain more than limited and temporary results. Hallam (2003) believes these issues are associated with the fact that people attempting to adopt these techniques do not know what they are trying to achieve. Although there are many tools and techniques there is not an overarching methodology for the application of Lean in a business setting, in terms of a step by step procedure that details how and when each of its tools are applied.

2.4 Error Proofing

A Poka-Yoke is a technique for avoiding simple human error at work (Shimbun, 1988). The term was first used by Japanese engineer Shigeo Shingo, and literally translates to ‘mistake proofing’. Shingo (1986) distinguishes between ‘mistakes’ (which are inevitable) and ‘defects’ (which result when a mistake

reaches a customer), and describes the aim of Poka-Yoke is to design devices which prevent mistakes becoming defects.

Shingo saw Poka-Yoke's as a means to move from 'judgement inspection', in which final inspection is used to distinguish between defective and non-defective products, to 'informative inspection', when processing is informed of whenever a defect is discovered so that it can be prevented from reoccurring, or 'source inspection' where defects are prevented by controlling the conditions that influence quality at their source. In essence, judgement inspections discover defects, while informative and source inspections reduce them (Shingo, 1989).

There are two types of Poka-Yoke – control and warning (Shingo, 1989). The former shuts down the production line in the event of a Poka-Yoke device being activated, whilst the latter alerts the worker when a defect has occurred. The choice between which type is implemented is influenced by the likely frequency of defects and the costs associated with their occurrence.

Casey (2009) provides clarity on the differences that make a Poka-Yoke a 'mistake proofing' device or an 'error proofing' device. A Poka-Yoke which prevents the operator from starting the value adding part of the function is an 'error proofing' device, as it is preventing bad product creation, whereas a Poka-Yoke that that is used to perform part inspection after the value added activity is a 'mistake proofing' device; the latter being consistent with Shingo's definition given above. In this sense, it is the position of Poka-Yoke device in relation to the value adding activity that determines its polarity.

Casey (2009) makes the case that error proofing devices are preferential because although mistake proofing devices prevent the continuation of the faulty production through the process, they are still reactive, whereas error proofing devices prevent the manufacture of defective parts in the first instance, removing the costs associated with handling the substandard products. Furthermore, he identifies three areas where error proofing must be focussed;

- Value added actions, such as the work of operators in assembly or manufacturing tasks

- Job set up elements, such as the alignment of tools and fixtures, or when kitting an area with components
- Processing parameters, such as critical process settings, which include temperatures, pressures, speeds, feeds or other parameters that govern the success of the process

Casey (2009) also states that consequently the best error proofing devices;

- Work constantly
- Are built into the natural flow of the operators
- Are simple and inexpensive
- Need only natural properties to function e.g. gravity

One drawback of using Poka-Yoke devices is that potentially valuable information about process variance may be lost, thereby inhibiting process improvement.

2.5 Systems Engineering & Process Modelling

2.5.1 Systems Engineering

A system is broadly defined as a set of interrelated components working together toward some common objective (Kossiakoff et al., 2011). This definition can encompass a myriad of examples from a weather satellite to a household guttering system, which demonstrates that systems exist at hugely differing levels of complexity and scale.

A manufacturing system is a typical input-output system which produces outputs through activities of transformation from inputs (Wu, 1994). The ‘common objective’ in this case is the output of the process, which is a component or product that conforms to the requirements set by its design, and the ‘interrelated components’ refer to the machinery, staff, supply chain and so forth that bring around the transformation.

2.5.1.1 Functional Analysis

Functional analysis can be seen to provide the backbone of systems engineering design (Campean et al., 2011). Functions are analysed by decomposing higher-level functions, into lower-level functions which results in a description of the system in terms of what it does logically and the performance required from it (Department of Defense, 2001). Deconstructing functions in this way creates a hierarchy that terminates at a level where the function can be achieved by hardware.

2.5.1.1.1 Axiomatic Design

Axiomatic design provides a standard conceptual framework to map system requirements through a series of 'domains'. These domains are, in hierarchical order, the Customer domain, the Functional domain, the Physical domain and the Process domain. There are functional hierarchies within each of these domains, created through iterative 'zigzagging' between adjacent domains, which define requirements at different levels within the system. This is demonstrated in Figure 2-2, adapted from Suh (1995), with a description of the characteristics represented by each of the domains for manufacturing.

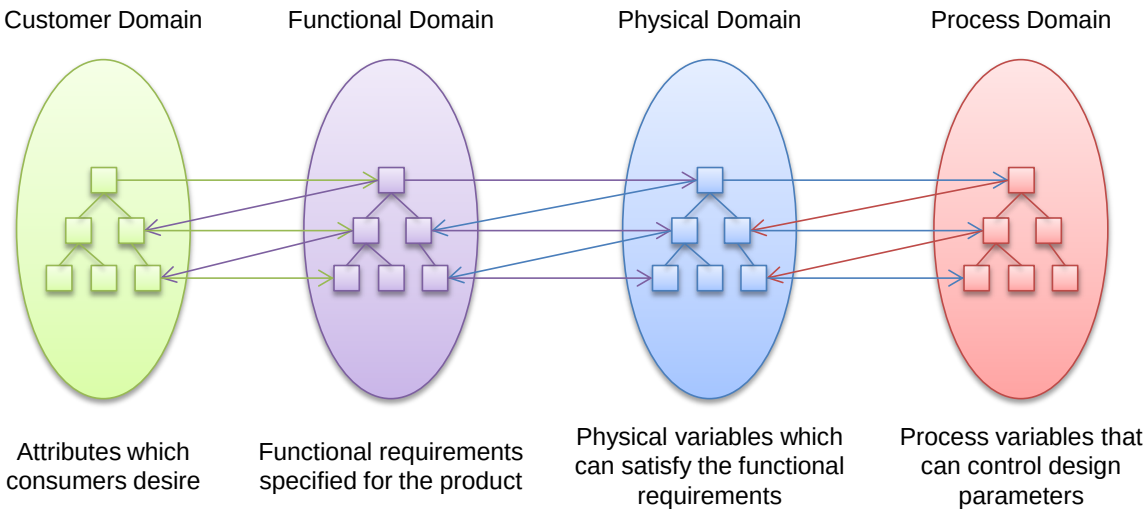


Figure 2-2 Domains and Functional Hierarchies in Axiomatic Design (El-Haik, 2005)

2.5.1.1.2 Functional Flow Block Diagrams

Functional flow block diagrams are also used to describe system requirements in functional terms. These are flow diagrams that link together a number of function blocks to show how they are sequenced in a system. A function block is a representation of a function that a particular collection of engineering systems and/or human actions are supposed to perform. The basic elements of a function block are the inputs, the internal states and the outputs (Papazoglou, 1998).

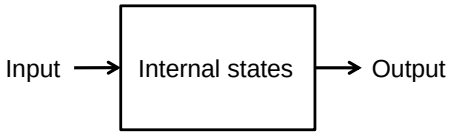


Figure 2-3 Simple Block Diagram

The Department of Defense (2001) provide the following guidelines for completing function flow block diagrams;

- Each functional block needs to stand for a definite, finite, discrete action
- Each level should have a consistent numbering format
- Lines connecting functions should indicate function flow and not a lapse in time
- Diagrams should be laid out so that the flow direction is generally from left to right

Figure 2-4 demonstrates how these functional block diagrams can be deconstructed to provide clarity. Wu (1994) recommends that each level has between three and six functions.

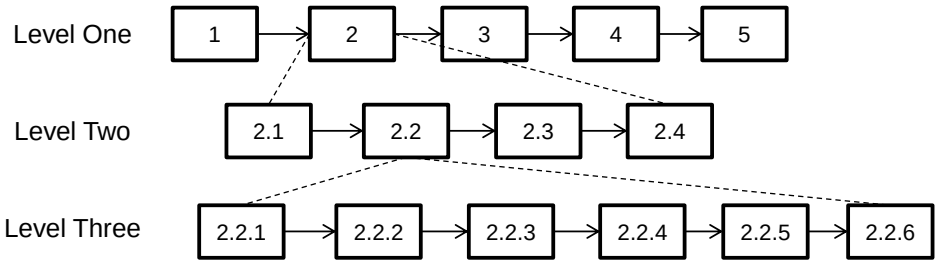


Figure 2-4 Decomposition through Functional Block Diagrams

When analysing complex systems, great care needs to be taken to select the appropriate level of detail for analysis. Failure to do so can result in isolation of one sub system from another, leading to an incomplete or distorted view of the systems behaviour (Bartolomei et al., 2012).

2.5.2 Process Mapping

Process Mapping consists of constructing a model that shows the relationships between the activities, people, data and objects involved in the production of a specified output (Biazzo, 2002). It is a popular method of visually representing a process in terms of its inputs, outputs and key activities. Consequently, the transformation of products within a process can be understood.

Process Mapping is used effectively to formally document and evaluate processes in order to reduce cycle time, reduce defects, improve consistency of operators, reduce new operator training time, reduce product variability and reduce hidden factory reworks (Breyfogle, 1999). Process Maps should be used to identify improvements and to locate significant or critical product and process characteristics, which allows them to be addressed in subsequent control plans (Chrysler, Ford and General Motors, 1995).

Despite widespread use, there are some potential pitfalls of Process Mapping and modelling recorded in the literature;

1. Process Mapping often results in differences between what is recorded and what actually occurs in reality (Bicheno, 2002).
2. Large amounts of time can be dedicated to creating Process Maps that are never used (Breyfogle, 1999)
3. Teams can get lost chasing ‘Syntactical correctness’ (Rosemann, 2006[b]) and spend overly long trying to create the perfect Process Map and may go beyond the true representation of the process (Pang, 2011).
4. Teams can have difficulty with complex processes which results in attempts to make overly detailed models (Rosemann, 2006[b]).

Mendling et al. (2008) provide some guidelines when producing process models. A 'Verb-Object' format should be used to describe operations as these are more easily understood. It is recommended that using as few 'elements' (operations) as possible and having only one start and one end point is beneficial as this simplifies the process. Furthermore, it is advisable to decompose the model if it becomes too large.

2.5.3 Cause and Effect Relationships

The Cause and Effect diagram was developed by Kaoru Ishikawa in 1943 and helps identify and document the causes and sub causes of a specific problem or effect (Clark, 2000). The tool is used to identify relationships between the effect and all the possible causes influencing it (Chrysler, Ford and General Motors, 1995).

Schippers (1999) provides a number of disadvantages of this tool when used to analyse processes;

1. The tool has to be continually redrawn when analysing multiple product characteristics. This is time consuming and does not facilitate the identification of interrelationships.
2. When the same cause affects more than one product characteristic it has to be written down on each diagram.
3. Cause and effect diagrams are difficult and inefficient when used in electronic form.

Consequently, Schippers (1999) has developed an alternative, which he refers to as a Process Matrix. This tool uses a matrix structure, which is popular in tools such as the 'The House of Quality' applied in Quality Function Deployment (Hauser and Clausing, 1988). The Process Matrix lists product characteristics along the top of the matrix and process factors across the side. Relationships between the characteristics and the factors are then recorded in the corresponding cells. This use of a matrix format is advantageous as it is easy to complete, efficient in space and has a clear structure. Furthermore, it is possible to add extra modules with ease and it can be drawn using standard software.

A similar structure is used for a Characteristics Matrix. A Characteristic Matrix provides a clear and simple description of the production process and the effect that successive operations have on the product (Carrión et al., 2007). Using a matrix structure applies the same benefits realised through the Process Matrix, but identifies relationships between product characteristics to process operations rather than process factors (Ford Design Institute, 2004). The Characteristic Matrix uses a key, or legend, of symbols to denote the nature of the relationships between the product and the process.

	Operations		
Product Characteristics	10	20	30
Hole Drilled	X	A	
Hole Tapped		X	A
Screws Added			X

Key
X – Characteristic created or changed
A – Characteristic has an effect on another

Figure 2-5 Simple Example of a Characteristics Matrix

2.6 Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) has been applied in an extensive range of industries (Liu et al., 2011) as a proactive tool to assess and improve the reliability of products and processes by discovering and correcting design deficiencies through the analysis of potential failure modes, effects, and mechanisms, followed by a recommendation of corrective action (Yang, 2007). FMEAs aim to define, identify, prioritise, and eliminate known or potential failures at an early a stage as possible (Bicheno, 2002).

2.6.1 Failure Modes

Kara-Zaitri, Keller, Barody and Fleming (1991) concisely define a failure mode as ‘any manner in which an item can fail’. In this definition the term item is used to describe a component, subsystem or system in terms of a product or a process. Kmenta and Ishii (1998) refer to dependencies within systems in their definition, by describing a failure mode as essentially an undesired cause-effect chain of events. Braunwart (2007) describes failure modes in to two main

groups – hard failures, where the item breaks or ceases to function and soft failures where the item continues to function but at less than ideal performance. Within these two categories there are four different types of failure mode (Ford Design Institute, 2004):

- Hard Failure Modes:
  1. **No Function** – System or design is totally non-functional or inoperative.
- Soft Failure Modes:
  2. **Partial/Over Function/Degraded over Time** – Degraded performance. Meets some of the function requirements, but does not fully comply with all attributes or characteristics.
  3. **Intermittent Function** – Complies but loses some functionality or becomes inoperative often due to external factors such as temperature, moisture, environment, etc. In effect, the starts/stops/starts again series of events.
  4. **Unintended Function** – This means that the interaction of several elements whose independent performance is correct adversely affects the product or the process. This will result in an unwanted outcome or consequence.

2.6.2 Types of FMEA

There are typically regarded to be four types of FMEA recognised by the literature (Stamatis (2005), Bicheno (2002), Yang (2007)) that can either be used in sequence, to form a hierarchy, or independently. A System FMEA is used at the design stage to analyse overall systems including the interactions between functions so as to minimise failure effects. A Design FMEA is used to minimise design faults before they are passed to manufacturing. The Process FMEA focuses on failures caused in the manufacturing process and should be applied during the development of all new processes and when modifying existing processes (McAndrew and O'Sullivan, 1994). Finally, the Service FMEA focuses on service failures.

The Ford Design Institute (2004) also recognise a Concept FMEA used to determine potential failures in the concept phases of designs and processes

and therefore aid in the selection of a winning concept. The Ford Motor Company (1996) provides training resources for Machinery FMEAs for assist in evaluating the reliability, robustness and safety of equipment during its design phase. However, this could be argued to be largely similar to a Design FMEA in principle.

Regardless of form, all FMEAs use a similar procedure and analysis sheet, as shown in Figure 2-6.

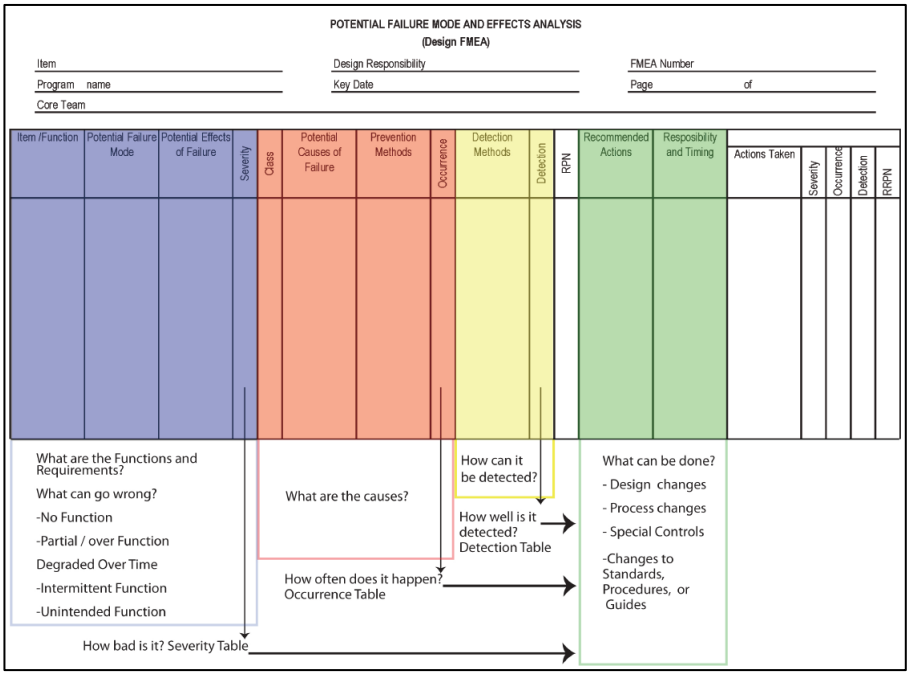


Figure 2-6 Typical FMEA document, in this case a Design FMEA (Quality One, 2012)

2.6.3 Risk Priority Number

The assessment of risk is one of the most important aspects of the FMEA process. The Risk Priority Number (RPN) is used as a measure of the relative risk of each failure, and is calculated by the product of three individual risk assessment criteria, Severity (S), Occurrence (O) and Detection (D), which are typically rated on a scale of 1 to 10, where 1 is the most favourable and 10 is the most critical case.

Severity is an assessment of the level of impact of a failure on the customer, Occurrence is how often the cause of the failure may occur and Detection is an assessment of how well the product or process controls detect the cause of

failure or the failure mode has occurred. The detection assessment is also used to measure the effectiveness of current controls to prevent the occurrence. Consequently, RPN values range from 1 to 1000. These are used to prioritise action and resource against specific failure modes.

2.6.4 Application of FMEA

Stamatis (2005) states that FMEA must begin as early as possible, as soon as some information is known, in order to maximised effectiveness as FMEA is one of the most important early preventative actions. Ford (1995) supports this idea, suggesting that timeliness is one of the most important success factors in FMEA implementation and that it is a 'before the event' rather than 'after the fact' exercise.

FMEAs must be completed by a team as the exercise should be a catalyst to stimulate the interchange of ideas between the functions affected. All of the team members should have some knowledge of the task at hand, the problem to be discussed, and direct or indirect ownership of the problem (Stamatis, 2005).

2.6.5 Advanced FMEA

Kmenta et al., (1999) developed an Advanced Failure Modes and Effects Analysis (AFMEA) as a methodology to analyse manufacturing process capability, which aimed to improve product quality, process efficiency and time to market. This method was originally developed by Eubanks et al., (1996) to enhance reliability at the early stages of conceptual design.

AFMEA uses a behavioural model that defines relationships between;

- functions
- states: preconditions ("what is required") and post conditions ("what is expected") of each function
- elements: physical entities that enable functions to achieve the desired post-conditions

Figure 2-7 shows the methodology for applying AFMEA, which begins with building a model to represent the manufacturing process as a causal sequence

of functions and states and is then utilised to identify and understand areas for improvement by inserting failures, simulating the effects and assessing the causes.

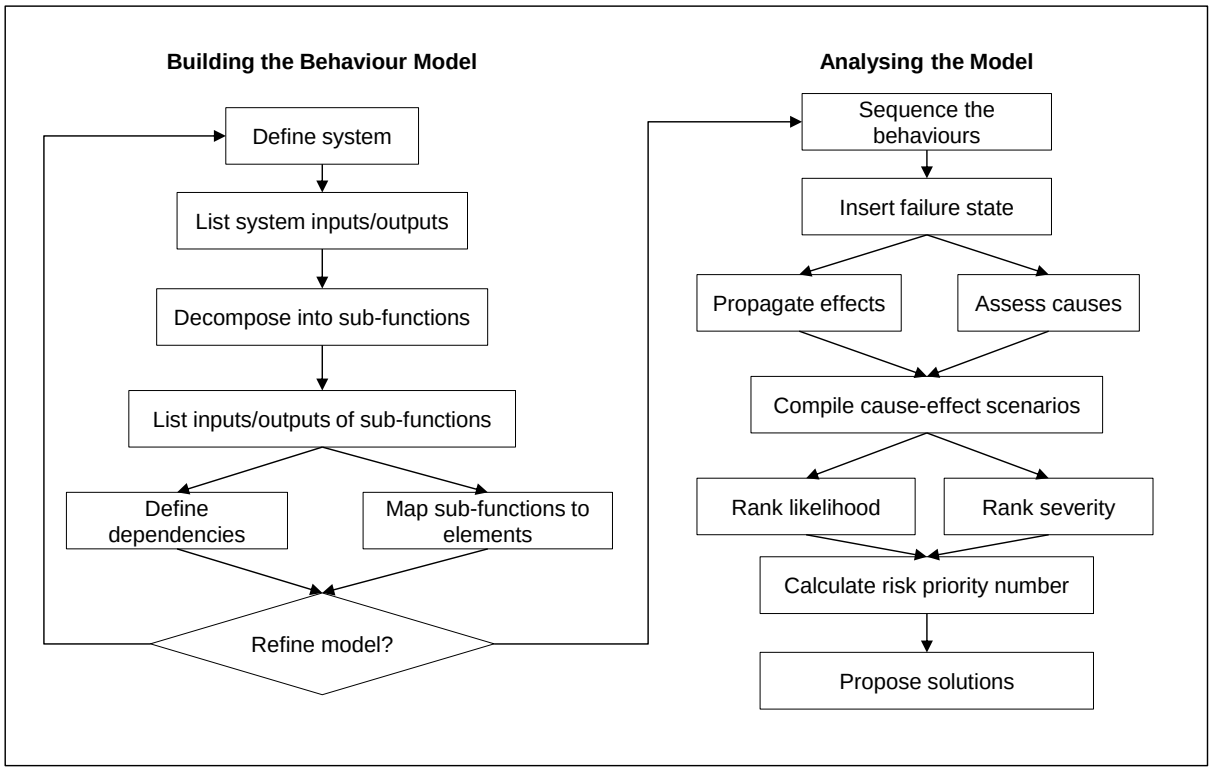


Figure 2-7 Flowchart for Advanced FMEA (Kmenta et al., 1999)

Through a workshop analysing an ultrasonic inspection process for titanium disks, Kmenta et al., (1999) compared the outputs of a free brainstorming approach with those of a version of structured AFMEA. Their findings showed that the structured AFMEA approach found a far higher number of process problems (119 to 32) and discussed that this method could be useful where a specific problem or error is unknown. Furthermore, this result was achieved with a facilitator that had less knowledge of the process than the brainstorming approach, from which they concluded that structured AFMEA was transferrable to other manufacturing processes and did not rely on process-specific expertise. However, it was also found that the AFMEA group tended to neglect the specifics of some failures, such as mechanical problems, as a result of the rigour of the method which limited the team's thinking to items closely related to the process model. Collected responses from the participants indicated that the AFMEA was advantageous in that it had a clear structure, logical approach and

an element of completeness, but disadvantageous due to its broad scope that limited depth and lack of accommodation for “off-the-wall” thinking (Kmenta et al., 1999). However, these studies have not covered corrective action that results from the identification of the failure modes and how this would be structured.

2.6.6 Shortcomings of FMEA

Despite a widespread application, particularly in the aerospace, nuclear and automotive industries, and well a defined methodology (Automotive Industry Action Group (2008), SAE J1937 (2009), Ford Motor Company (2004)) there are many reported shortcomings with FMEA;

- FMEAs are highly labour intensive and there is a tendency to produce large, cumbersome documents (Bell et al., 1992)
- FMEAs are perceived as a difficult, laborious and ‘boring’ technique (Kara-Zaitri, Keller, Barody and Fleming, 1991)
- The time scale required to complete the analysis often exceeds the design and development stage (Hawkins and Woollons, 1995)
- FMEAs are not used to affect design decisions as failure causes are not often defined (McKinney, 1991)
- FMEAs are often seen to be ‘just more paperwork’ and as a result no benefit is expected from them (Johnson and Khan, 2003).
- Without an organized approach to identifying failure modes, the analysis can become subjective based on experience level of the engineers (Kmenta and Ishii, 1998)
- After the initial high severity risks have been avoided, or the ‘critical few’ as Casey (2009) describes them, there is an issue of scope, where the abundance of lower risk failures become so large that that FMEAs no longer provide an effective prioritisation. Casey (2009) refers to this as ever increasing opportunity.
- The validity of RPN as a method of prioritization is questionable. The three risk factors are difficult to be precisely evaluated, the relatively importance of S, O and D are not taken into consideration and different

combinations can render the same RPN whilst the hidden risk implications can be totally different. (Liu et al, 2013)

2.7 Failure Mode Avoidance

Inspired by Clausing's (2004) pragmatic definition "reliability is failure mode avoidance", Failure Mode Avoidance (FMA) promotes a strategic focus on early identification of potential failure modes and development of robust countermeasures. The FMA framework discussed by Campean et al., (2013) offers a consistent approach for systems engineering design analysis, facilitating early discovery of failure modes through the use of a structured sequence of proven engineering tools that are built around a central FMEA. In essence, the philosophy is that identifying potential failures early, when the opportunity for change is greatest and the cost is lowest, is ultimately a matter of common sense engineering complimented with a structured framework and a proven toolset (Campean and Henshall, 2009).

2.7.1 The Failure Mode Avoidance Process

The FMA framework consists of four higher level process steps, as illustrated in Table 1, each with a clear objective and supported by existing engineering tools.

The FMA process is based on the premise that in order to identify the manner in which a system can potentially fail to function it is necessary first to understand how the system functions (Campean and Henshall, 2009), which is achieved in the first step. Once the potential function failure modes have been identified then the effects and causes of failure can understood in second step. The third step determines the cause of the failure mode. Finally, when all the mechanics of each failure mode is understood fully, robust countermeasures can be developed and implemented.

FMA Process Step	Engineering Tools
1.Understand how the system functions	Boundary Diagram Interface Matrix System State Flow Diagram Function Tree
2. Identify how the system fails to function and the effect of failure	FMEA
3. Determine the cause of failure	Function Fault Tree P – Diagram
4. Develop and verify countermeasures to failure	Robustness Worksheet Design Verification Worksheet Design Verification Plan

Table 1 FMA Process Steps and Engineering Tools

2.7.1.1 Step 1

In order to develop a thorough understanding of the functioning of a system, FMA employs a series of synergistic tools. A System State Flow Diagram (SSFD) is used to provide a comprehensive function based decomposition by mapping the flows of energy, material and information through the system (Campean et al., 2013). SSFD provides an identification of discrete states of energy within the system, identification of the functions required from the system to transition between these states, and identification of the design elements that would deliver these functions. The functions that have to be achieved by the system in order to satisfy this energy flow are then mapped onto the SSFD, decomposing into a functional hierarchy to a level that can be achieved by hardware. This allows a function tree to be developed.

With these factors identified the system is defined using a Boundary Diagram. Defining the boundary of a system is the process of identifying the signals to the system, the outputs from the system and the noise sources that disturb the system (Ford Design Institute, 2004) (Yang, 2005). FMA uses the Boundary Diagram to identify the internal and external interfaces (noise factors) and other systems that interact with the main systems function. Exchange at interfaces is

important because they can influence the delivery of the main function of the system (Campean et al., 2013).

The Interface Analysis Table (IAT), developed from the Interface Matrix and Design Structure Matrix (DSM) used in industry (Webb, 2002) (Browning, 2005), is used to document the nature of the exchange at the interface, a functional requirement for managing the exchange at the interface and an evaluation of the effect of the interface on the main function of the system (Campean and Henshall, 2013).

2.7.1.2 Step 2

With a rich understanding of the functioning of the system, function failure modes are systematically identified using an FMEA. As a document, the FMEA is typical of those described in Section 2.8, but the difference is that it is populated by the information contained in the preceding FMA documents. For example, interface functions, documented in the IAT, provide the possible root causes of a function failure mode recognising that failure to manage an interface function is likely to cause a system failure (Campean et al., 2013).

2.7.1.3 Step 3

In FMA, the FMEA is also supported by P – Diagrams and Function Fault Tree Analysis. A P – Diagram is useful to understand a particular subsystem and how noise factors can create error states (Johannesson et al., 2012).

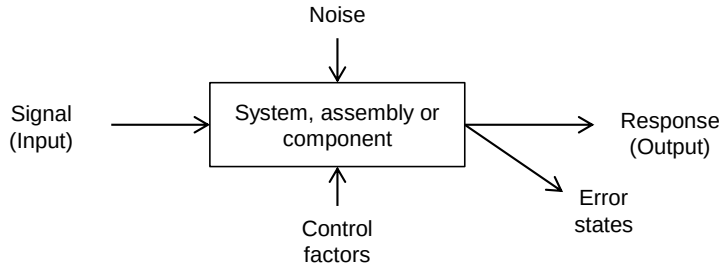


Figure 2-8 P Diagram

As much of the information on the P - Diagram is previously identified, particularly on the Boundary Diagram, it is relatively straightforward to generate but is powerful in bringing together factors that potentially have a beneficial or

detrimental effect on the system, and in a clear graphical form (Campean and Henshall, 2009). The P – Diagram is particularly useful in identifying failure modes that are caused by variability, and that are associated with a lack of robustness in the system (Campean et al., 2013).

The causes of failures are also identified using a Function Fault Tree. A fault tree is a graphical representation of the logical relationship between a system failure and a hierarchy of events (Campean and Henshall, 2008). In FMA it is created as a mirror image of the function tree and is used to map how potential failures can occur in the system and what their effects are. Once this is known, this information can be fed into the FMEA under 'Potential Causes of Failure' and a score representing how likely these are to occur can be given.

2.7.1.4 Step 4

With the potential failure modes identified and their causes analysed, robust countermeasures can be designed and verified to prevent their occurrence through noise factor management. The noise factors are prioritised by assessing their severity and likelihood of occurrence, as well as the current state of knowledge of the noise factor effects (Campean and Henshall, 2009).

Populated with information from the P – Diagram, a Robustness Worksheet is used to categorically assess the options for addressing each of the noise factors. These range from doing nothing, if it is decided that the existing design is good enough to avoid failure, to implementing a design change where there is doubt that the current design is adequate.

If countermeasures are required, established and implemented these need to be verified and proven effective (Campean and Henshall, 2009). The noise factor that is being addressed by the countermeasure needs to be included in any verification study in order to prove that they are effective. A Design Verification Plan is then used to manage these studies, detailing which tests are to be conducted and the acceptance criteria.

As with the other steps in the FMA process, the FMEA plays a central role in this step by managing the overall process (Campean and Henshall, 2009). The information on countermeasure development is documented on the FMEA

either under ‘Current Controls’ when the countermeasure is pre-existing, a similar design or when it has been deemed that ‘doing nothing’ is a suitable action, or under ‘Recommended Actions’ when the implantation of a developed countermeasure is required.

2.7.2 Strengths and Weaknesses

The FMA paradigm has been proven effective in industrial case studies (Campean et al., 2011, Campean et al., 2013) and has had a strong uptake in the automotive industry as a strategy for enhancing effectiveness of the product development process.

Campean and Henshall (2012) provide feedback from teams in a number of their publications, in which they have implemented the FMA approach in industry case studies. This feedback highlights the following positive aspects;

- The structured approach to the process removes the reliance on brainstorming and delivers a more objective, impartial and comprehensive analysis
- The approach is portable and can be applied across multiple domains
- The strong integration of the process through the information flow between the tools
- The FMEA was more straightforward to complete
- FMA provided a strong framework for gathering comprehensive knowledge about the system being designed

Teams still found that following the FMA approach was still an expensive activity and was not without its own challenges. Some teams found that maintaining an adequate level of resolution for the analysis was difficult, as a result of team members from different engineering backgrounds contributing different levels of understanding of the problem. However, it was found that through the functional analysis a consistent level of resolution was achieved (Campean et al., 2011).

Campean et al. (2011) also state that the Interface Analysis was perceived as being challenging and time consuming, as it was tackled by a team with no prior

experience to the tool. However, the team were still able to identify potential exchanges at interfaces and recognised that without the full functional analysis some of these would have been overlooked. The time spent on developing the interface analysis is redeemed later in the product development process as late engineering changes and their associated costs are mitigated (Campean and Henshall, 2013).

Although the FMEA was more straightforward to complete, it still required significant effort from the team in regards to the supporting tools. However, it was felt that this effort was worthwhile, providing the structure in terms of setting requirements for components, developing countermeasures and so forth, and as a result it was perceived as an effective way for managing failure modes and not as 'just another thing to do' (Campean et al., 2011).

The FMA approach requires a shift in resource allocation from failure resolution upstream towards failure avoidance, which is a large challenge to overcome in engineering organisations. A fundamental aspect of this challenge is associated with cultural norms of reactive action or 'firefighting' (Campean and Henshall, 2013).

2.8 Statistical Quality Improvement Methods

2.8.1 Six Sigma

Six Sigma is a quality approach that originated in Motorola in 1987 who called their approach 'Six Sigma' when winning the 1998 Baldridge Award (Bicheno, 2002). Its strategy involves the use of statistical tools within a structured methodology (Breyfogle, 1999) in order to reduce variation in processes and services. Schroeder et al., (2008) discuss the various disparities in the definitions of Six Sigma, from both an academic and practitioner perspective.

In statistics, the Greek letter 'σ' (Sigma) refers to the standard deviation; a measure used to quantify the amount of variation within a set of data. Simplistically, it refers to the average difference between a sample of data and its mean. Six Sigma aims to develop processes that are stable to such a degree that the required upper and lower specification limits are six standard deviations

from the mean output. In relation to the standard normal distribution this equates to 3.4 defective parts per million and demonstrates a highly capable process. To this end, the fundamental principle of Six Sigma is to take an organisation to an improved level of Sigma capability through the rigorous application of statistical tools and techniques (Antony et al., 2003).

2.8.1.1 Methodology

DMAIC, an acronym that stands for Define, Measure, Analyse, Improve and Control, is a structured improvement procedure used by Six Sigma (De Mast and Lokkerbol, 2012), where each of the letters correspond to a phase. De Koning and De Mast (2006) state that most accounts of the Six Sigma methodology agree on this phase structure, but descriptions of the steps they comprise of and the tools they implement diverge. Consequently, through a thorough study of reputable sources, including Breyfogle (1999), Harry (1997) and Hahn et al., (2000), they have produced a consistent rationalised construction of the Six Sigma methodology, shown in Table 2 as reproduced by De Koning and De Mast (2006) where 'CTQ' refers to a process's Critical-to-Quality characteristics and 'X' refers to a causal influence factor.

Phase	Generic Objective
Define	**Problem selection and benefit analysis** **D1** Identify and map relevant processes **D2** Identify stakeholders **D3** Determine and prioritize customer needs and requirements **D4** Make a business case for the project
Measure	**Translation of the problem into a measureable form, and measurement of the current situation** **M1** Select one or more CTQs **M2** Determine operational definitions of CTQs and requirements **M3** Validate measurement systems of the CTQs **M4** Assess the current process capability **M5** Define objectives
Analyse	**Identification of influence factors and causes that determine the CTQs behaviour** **A1** Identify potential influence factors **A2** Select the vital few influence factors
Improve	**Design and implementation of adjustments to the process to improve the performance of the CTQs** **I1** Quantify relationships between Xs and CTQs **I2** Design actions to modify the process or settings of influence factors so that CTQs are optimised **I3** Conduct pilot test of improvement actions
Control	**Empirical verification of the project's results and adjustment of the process management and control system in order that improvements are sustainable** **C1** Determine the new process capability **C2** Implement control plans

Table 2 Six Sigma Methodology

2.8.1.2 Applications of Six Sigma

Despite, being described as a 'full-on company fad' by some critics (Clifford, 2001), Six Sigma's potential is demonstrated through successful applications in manufacturing organisations such as Motorola, Raytheon, General Electric, Honeywell, Johnson and Johnson and Texas Instruments who report cost savings and increased efficiency (Kwak and Anbari, 2006).

Strengths of Six Sigma include (Antony, 2006);

- Clear focus on achieving measureable and quantifiable financial returns
- Emphasis on the importance of data and decision making rather than assumptions
- Dedicated tool set, each with a how, why and when

2.8.1.3 Limitations of Six Sigma and DMAIC

Breyfogle (1999) describes that Six Sigma implementation can either be the best thing that happens to a company or it can be found to be a dismal failure and that it all depends on the implementation. According to Antony (2004), the right selection and prioritisation of projects is one of the critical success factors of a Six Sigma program, but this tends to be based on pure subjective judgement. This is especially the case when quality data is unavailable at the start of a project. Nonthaleerak and Hendry (2008), found that project selection is usually based on over emphasis of financial savings criteria, conducted in the Define phase. This had a negative impact on the overall project length as an overly long time was dedicated to this phase. Furthermore, Chakravorty (2009) finds that the DMAIC process proceeded more effectively when the problem was easily and clearly defined, as opposed to proceeding irrationally when not clearly defined early in the process. This resulted in speculation of root causes and proposed solutions through 'trial and error' without solid justification.

In regards to the Control phase, it was found that difficulties are encountered in setting up effective means to sustain improvement results at the end of a project and that large organisations that demonstrate success in this area 'all have a good foundation in a quality system' such as ISO9000 which ensures control plans are in use and maintained effectively. Nonthaleerak and Hendry (2008)

conclude that having a foundation in a quality system is advantageous when adopting Six Sigma. Anthony (2004) alludes to frustration experienced as the solutions driven by the data are expensive and only a small part of the solution is implemented at the end.

2.8.2 Statistical Process Control

Statistical Process Control (SPC) refers to the use of statistical based techniques for the control of a process that transforms inputs into outputs (Oakland, 2003). SPC aims at achieving good quality in manufacture through prevention rather than detection, by controlling the process, or the machine, which makes the product. The principle is that if the process is good, then the outputs will automatically be good (Bicheno, 2002). Alternatively, if the process goes out of control, it can be stopped before any further defects are made.

SPC uses a number of different tools to identify and prioritise relationships, such as Pareto analysis, tally charts, histograms and scatter diagrams, but Control Charts are the most prevalent method of monitoring process performance (Oakland, 2003).

2.8.2.1 Control Charts

Control Charts are used to study how a process changes over time and to determine if that process is in a state of statistical control (Tague, 2005). The main Control Charts are the ‘X bar and R chart’, which are used to monitor the mean and range of the sample taken (Bicheno, 2002). A characteristic of the process that is related to the quality of the product is selected and measured according to a Data Collection Plan. These measurements are used to calculate the mean and the range of the data set, which are subsequently plotted on a line graph. Based on the data sampling frequency and sample size upper and lower control limits are set that determine when a process is out of statistical control and intervention is required (Oakland, 2003). Furthermore, the data can be analysed to identify instability in the process by evaluating abnormal distribution patterns (Asaka, and Ozeki, 1990).

- **Sequence** - More than seven data points on one side of the centre line

- **Bias** – More data points on one side of the line, but less than seven consecutively
- **Trend** – A steady rise or fall of seven of more consecutive data points
- **Approaching the limit** – Two of three consecutive data points near the control limit
- **Periodicity** – The position of data points rises and falls in a periodic waveform

Through analysis of the data, sources of variations can be identified and understood which allow improved process control and management. For instance, trends of data can suggest when tools are becoming worn, or when routine maintenance of machinery is required e.g. oil changes.

Doty (1996) provides nine steps for constructing Control Charts;

1. Select the quality characteristic
2. Develop a quality plan
3. Select the type of Control Chart
4. Choose the proper subgroup size
5. Collect the data
6. Determine the trial control limits and the chart midpoint
7. Determine the revised control limits and chart midpoint
8. Construct the revised Control Chart
9. Continue to use the chart

2.8.2.2 Process Capability

Process capability studies are used to assess the performance of a process relative to its specification criteria (Breyfogle, 1999). In essence, process capability asks ‘Is this process able to do what is asked of it?’. Process capability studies differentiate between conformance to control limits, determined by the natural variation of the process, and conformance to specification or tolerance limits, which are ultimately set by the customer through design. In order to be capable, the natural spread of the process must lie within the specification limits. If this is not the case then defects will occur.

2.8.2.3 Shortcomings of SPC

SPC can be difficult to implement in low volume manufacturing as there may not be enough data to accurately estimate process parameters (Woodhall and Montgomery, 1999). Also, these methods can be difficult to implement when staff members do not possess the statistical knowledge required in order to use the tools effectively.

Breyfogle (1999) finds that collection and reporting of data can be expensive, and 'should not be prioritised over process improvement efforts'. Furthermore, he states that organisations only focus on measuring the output of the process when applying Control Charts, which does not allow defects to be avoided, only detected. Rather, more emphasis should be put on measuring process inputs and stopping production when these go out of control.

Finally, the bottom line is that SPC does not ensure customer satisfaction. A poor product can still be made to all the manufacturing requirements (Oakland, 2003).

2.9 Summary

This section has given an overview of the key areas that are associated with this research. Firstly, quality has been defined and its meaning explored in a manufacturing context, which has allowed higher level systems that are used by businesses to manage quality to be studied. Also, clear meanings have been obtained for relevant terminology associated with process analysis.

The concept of Lean has been covered by studying its underlying principles and the different forms of waste that can exist. Instances of where Lean has been adopted and applied have also been investigated that show that it is a broad applicable philosophy. Also, the shortcomings and issues published in the literature have been reviewed.

Error proofing, or Poka-Yoke, techniques have been explained, with attention given to the difference that can exist between them. Best practice has been identified that allows the user to best design a device to prevent mistakes occurring.

The fundamentals of System Engineering and Process Modelling have been explained, and the guidelines for best practice and potential weaknesses of these methods have been identified. The mechanics of FMEA have been detailed, including the various types of failure mode, the different forms of FMEA that can be used, improvements that have been made to the FMEA procedure and the potential shortcomings that have been experienced with its use in the field.

The Failure Mode Avoidance framework has been explained, including the principles and tools that it comprises, which has allowed the strengths and weaknesses of this approach to be discussed. Finally, statistical quality improvement methods, such as Six Sigma, have been identified and their methodologies examined in order to understand the issues that have been found with these techniques so that they can be addressed in the research.

3 Research Methodology

3.1 Review of Current Practice

Due to the pressures associated with increasing production rates whilst simultaneously reducing manufacturing costs that are described in Chapter 1, the Company has embarked on a Lean transformation. Table 3 provides an overview of the current state and the vision of the future state of the Company's manufacturing operations, demonstrating the overall aims of the transformation as a case of 'before and after'.

Current State	Future State
• No levelling of schedule • Parts made to schedule not demand (Push not Pull) • No visual controls or management • No safety culture or controls • No Poke Yoke/Root cause analysis culture • Disorganised,- No 5S culture • No process standards • No continuous improvement culture • No flow • Large amounts of inventory & work in progress • Machines breaking down • No ownership • No teamwork • 'Waste' everywhere	• Close coupled sequential processes • Single piece flow production • Visually controlled environment • Orderly, safe and clean – 5S • Controlled inventory/WIP • Clear targets and metrics • Quality and control in all processes • Quick equipment changeovers • Controlled buffers • Root cause analysis • Kaizen driven problem solving • Balanced workstations • Standard operations • Minimum waste • Shorter lead times • Value added culture with operators • Process confirmation

Table 3 Current and Future State of the Company's Manufacturing Operation

At the time of this project, the Company was going through this transition. Some aspects of the change have been successful, whereas others are proving more challenging and exposing weaknesses in the Company. These weaknesses are compromising the effectiveness of the implemented changes. Section 2.3.6 of the literature review suggested that in order for full and continued exploitation of Lean techniques, the philosophy has to be realised as a whole and it is perceived that this scenario is being realised in this instance.

Through observations made by the Author, there was clear visual evidence of the initiatives that have been successfully embraced by the Company. The adoption of a 5S standard, visual control and communication of the performance and status of production areas, minimum inventory, Kanban

systems, and a sequential, single piece flow line are all in place. There was an apparent cultural emphasis on continuous improvement with kaizen processes in operation.

Furthermore, daily reviews, dubbed DSUMs (Daily Start Up Meeting) were common place. These were conducted in individual production areas, such as ‘Front Fuselage Zone 1’, ‘Environment System Loom Assembly’ and ‘Flaperon SPF’, are led by the area supervisor and involve the entire team. Having attended multiple DSUMs the Author has identified that meetings were based upon a consistent structure of Safety, Quality, Cost, Delivery and People (SQCDP). Under each of these topics performance metrics are shared, potential issues and resurrections are discussed and relevant Company information disseminated. It has also been observed that these meetings are hierarchical within the Organisation, as the supervisor will report into a higher level WSUM (Weekly Start Up Meeting) with their managers in order to provide vertical information transfer through the Business.

However, there were areas of the future state vision that had not made the transformation required to exercise a deeper cultural change and yield a holistic improvement to the Company. These aspects are those associated with the individual control of parts and processes at a manufacturing level. In particular, and in reference to Table 3, the present weaknesses are related to the quality and control in processes and root cause analysis, which result in high levels of defective parts, ineffective prevention process improvement actions and ultimately continued waste and escalated costs of production. Fundamentally, improving visual management and flow is futile whilst incorrect parts are made; making the defective parts efficiently does not quantify a valid improvement.

The Author found that control plans did not exist in the same manner as illustrated in Section 2.1.2.3 of the literature review. Instead, control measures were administered in the general manufacturing planning by reference to generic specifications that relate to each of the manufacturing processes. The reliance is then on the operator or fitter to reference these specifications during manufacture. Anecdotal evidence suggests that these were not regularly consulted by the work force.

On the event of non-conformance, components were managed through a procedure known as the Material Review Board (MRB). This procedure consists of examining the component, identifying corrective action and subsequently conducting necessary rework or scrapping the item. If it was judged that a component has failed for the same reason on more than three occasions, then a root cause analysis would be recommended.

This describes a reactive approach to quality and conformance. Production operations rely on reference to broad standards and provide operators freedom to manufacture parts based on prior knowledge and experience. Part conformance was proved through inspection methods and corrected if possible. During planning, potential failures were not considered in detail and therefore the control methods in place are generalised and were not specific to the manufacture of distinct components. Consequently, quality control was more prevalent than quality assurance.

However, there was evidence of improvement activities and initiatives within the Company. For instance, Process Mapping exercises were held in cross functional groups as attended by the Author. These appear to have been effective for a shared understanding of processes by the stakeholders, but improvement action and continuing monitoring and improvement did not appear to stem from these methods, as if completing the task was its own reward. Furthermore, they were at a business process level and therefore did not effectively capture the characteristic detail of the components or the manufacturing methods by which they were created and thus overstepped any means to control the manufacture of complex aerospace parts.

In terms of process variability reduction, the Company had a ‘Producability’ team which conducted Six Sigma projects. However, it would seem that these projects were not heavily bought into by the Business on the whole, illustrated by the fact that the team comprised of 6 permanent staff that practice the associated DMAIC technique in a business of roughly 9000. Furthermore, Nonthaleerak & Hendry (2008) state that a typical Six Sigma project will last between 4-6 months. As it is not uncommon that these projects were ongoing after 12 months, without demonstrating any significant implementation of

process improvement, it suggests that there may have been issues associated with scoping these activities.

There was also evidence to suggest the occasional use of FMEAs. However, in the Author's experience these instances had been reactive, stimulated as a response to an overly defective or costly area of manufacture, rather than during preliminary design and development, or had been led by machinery suppliers in order to assure delivery of the required capability. Although conducted as a team consisting of relevant process stakeholders, they were performed through brainstorming activities and did not apply associated tools in order to enhance the capture of failure modes. In addition, formal control plans were not developed as a consequence. The size of these documents was in the order of 500 line items and above, and similar to the mapping exercises, they were not performed at a level that captures detailed part or process characteristic data.

In summary, although proven practices existed, they were often performed ineffectively, in isolation from one another and without clear intent. The evidence suggested that these activities were not correctly scoped in order to allow the development of an appropriate understanding that facilitates improvement action capable of fostering suitable control at a part manufacture level. Furthermore, there did not appear to a standard practice for the use of these tools that was appropriately governed and applied.

Consequently, within the Company there exists both an opportunity and an appetite to implement a new strategy to ensure that production is in control to allow the simultaneous increase in manufacturing rates and decrease in associated costs required to remain competitive in the global aerospace market.

3.2 Analysis of Requirements for MFMA Process Development

The literature has provided an overview into some of the tools and techniques that can be applied to enhance control over processes and parts that allow improvements in quality to be made. The Company required a means to apply these techniques in order to facilitate a step change in the control of their manufacturing operations and move away from the traditional methods used in the aerospace industry which are associated with reliance of craftsmanship

skills and lengthy and expensive corrective actions. This would also allow the Company to fully realise the benefits of the changes that have already been implemented.

Throughout Section 2 methods and tools have been provided for establishing control and facilitating improvement in both product design and process operation. FMEA, as discussed in Section 2.6, is a popular tool and logical in its approach towards improving robustness, but it has many underlying weaknesses, particularly associated with its reputation for being an arduous activity and not leading to corrective action. P Diagrams, Boundary Diagrams, Cause and Effect Analysis and Process Mapping are all effective techniques to understand how a process functions, and the relationships that are pivotal and detrimental to this effect, but the benefit of these practices is limited when they are used in isolation.

In terms of more overarching processes Six Sigma, Advanced FMEA, FMA and APQP provide established examples. Six Sigma has had a wide uptake, has demonstrated success and uses a range of process tools, but it has weaknesses associated with project selection and scoping, particularly when the process is ill defined, and the outputs of the effort are difficult to implement without a robust quality system. Advanced FMEA demonstrates improvements over the traditional FMEA procedure, providing a more systematic approach to failure mode identification, but it is seen as overly rigorous and consequently detrimental to the ‘free thinking’ of the team. Furthermore, the method provided does not illustrate a direct input into control planning and ‘closing the loop’; the final step, as shown in Figure 2-7, is broadly titled ‘Propose Solutions’. FMA uses a structured approach to scope and manage improvement actions through the use of a top-down functional decomposition, typical of systems engineering, and prescribes a series of proven tools. However, it has been developed and tested / validated in a context of design of products and systems rather than processes. APQP gives a high level, end to end method to product and process planning, but does not have the detailed structure and information flow of FMA or Advanced FMEA that is beneficial for implementation.

Consequently, there was a requirement for a procedure that can combine the strengths of these processes and tools described. FMA possesses a structure at a similar level to Advanced FMEA, captures a holistic view akin to APQP, and could be used to provide scope for improvement strategies like Six Sigma and other process capability studies. Furthermore, in one form or another, it utilises proven engineering tools ensuring that their output is used effectively which provides context, rationale and greater benefit when compared to an isolated application. This is achieved by a strong information flow between the tools. As a result, the FMA methodology and philosophy will provide the backbone for a new process that will be developed for application on manufacturing process design and control.

In order to achieve this requirement, the methodology needed to be outlined, trialled and proven effective to allow for adoption by the Company. In the context of the Business the overriding requirement was to develop a methodology that is capable of reducing costs through improvements in part quality that are created by robust process control. Therefore, in summary, the methodology was based on the principle, structure and approach of the FMA framework but needed to be customised for application in a manufacturing process environment.

3.3 Proposed Manufacturing Failure Mode Avoidance Framework

The fundamental philosophy that underpins FMA is that ‘robustness is failure mode avoidance’. In essence, robustness is preventing any opportunities for failure. The key strengths and novelties of FMA have previously been discussed, but for clarity the characteristic features of the process that enable its success and will subsequently be adopted for a Manufacturing Failure Mode Avoidance (MFMA) framework are as follows;

- High level steps with clear objectives to provide an overarching structure to the process
- Dedicated, proven engineering tools used to achieve each objective, which scope and define engineering efforts
- A coherent flow of information between the tools that facilitates the analysis and allows it to be managed effectively

- A functional approach to the analysis, which has proven successful at identifying failure modes

To be effective, a MFMA framework needed to inherit these characteristics to achieve the following objectives;

- Map complex aerospace manufacturing processes at a functional level
- Identify all process failure modes and the mechanisms of failure
- Provide clear scope and objective for process improvements
- Define methods for specific process controls

The MFMA framework was developed by examining each of the higher level steps of the FMA framework, their objectives and the tools that have been used to achieve them and devising an equivalent step for manufacturing process analysis and improvement based on the literature. An overview of the MFMA framework, demonstrated in tandem with the FMA framework, is illustrated in Figure 3-1.

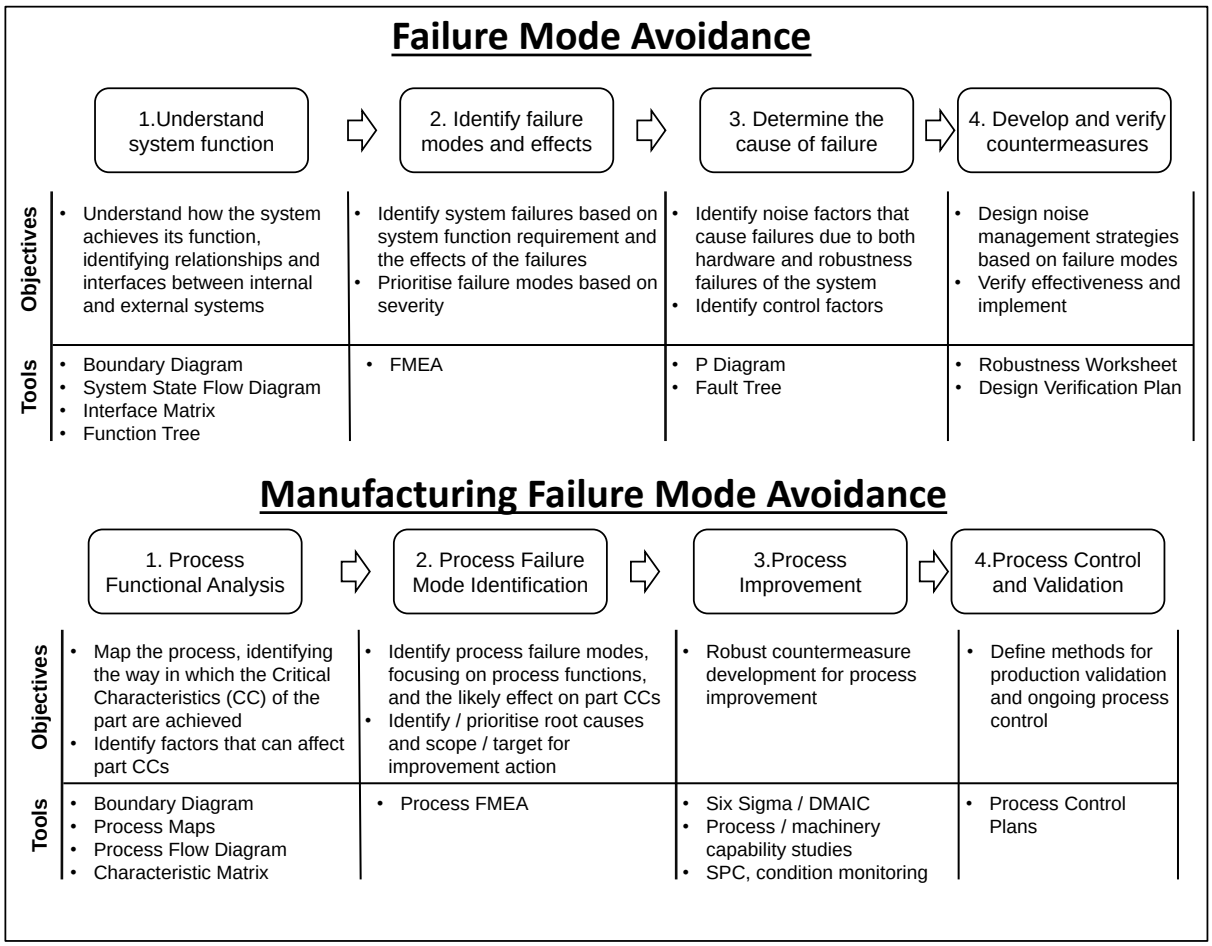


Figure 3-1 Overview of the FMA and MFMA frameworks

3.3.1 Step 1

The first step of the FMA framework aims to understand how the system performs its function. This is achieved through synergistic use of a Boundary Diagram, System State Flow Diagram, Interface Matrix and a Function Tree. Together these tools define the scope of the analysis, identify the flows of energy between the components and records their states at instants between them, analyse the intentional and unintentional relationships between the components and provide a cascade showing the functional hierarchy within the system. It is quoted in the literature that these tools can be used in any order.

A corresponding objective of the first step of a MFMA framework was to understand how the process achieves its function. As discussed in Section 2.5 of the literature review, a process can be modelled as a system with inputs and outputs, using functional block diagrams. Consequently, the process can be defined at the highest level using a single block. As a result, a Boundary

Diagram is used, scoping the analysis in the same way as it is used in FMA. However, in this case, the Boundary Diagram records the transformation of the part, rather than the energy flows within a system. In doing this, the Boundary Diagram also captures the interfaces to the process that are external to the boundary.

Next, where FMA uses a System State Flow Diagram to identify the internal flows of energy, the process can be deconstructed into individual steps using a functional Process Map. This combines the best practice of Process Mapping and functional block diagrams, discussed in Section 2.5.1.1.2 and Section 2.5.2, to separate the process into a flow of discrete functions, and allow the part's state to be recorded at the instants between them. The complexity of the processes is managed through this decomposition. As advised, the functions are described using a 'Verb Object' convention, flow from left to right, refrain from mapping time lapse activities and are completed to a level which can be engineered.

A Process Flow Diagram adopts the process structure defined through the functional Process Map, adding further detail relating to the transformation by cataloguing the part and process characteristics that are used or changed at each step. This should include the magnitude and metric of the characteristic where possible. This tool provides the first opportunity to list the sources of variation that are known to be present at each operation. Figure 3-2 shows an example of the Process Flow Diagram, populated using a fictitious manufacturing process, to demonstrate the format of this document and the information captured.

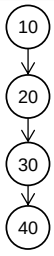
Sources of Variation	Process Function	Graphical Flow	Part Characteristics	Process Characteristics
Position within Clamp Contamination	Locate Item 1		Orientation (X,Y, Z) Position (mm)	Clamp Clamp Pressure
Drill Sharpness Material Hardness	Drill Hole		1 x M8 Hole (mm)	Drill Drill Speed Drill Feed Rate
Insert Size Contamination	Locate Insert X		Insert X in M8 Hole	Pressure Insert Angle
Contamination	Screw in Item 2		Item 1 and Item 2 Assembly	Angle of Entry Torque

Figure 3-2 Example of Process Flow Diagram

Where FMA uses an Interface Matrix to identify casual relationships between the elements of the system, MFMA uses a Characteristics Matrix to identify and understand the relationships between the part and the process characteristics. The material associated with these characteristics flows inwardly from the outputs of the previous mapping exercises, establishing the distinguishing information flow that is one the foundations of the FMA framework. This document is an enhanced version of the example provided in Figure 2-5, as shown in Figure 3-3 using the same fictitious example for demonstration as in the previous Figure.

Whilst conserving the original tabular format with the part characteristics on the vertical axis and the process operations on the horizontal, this tool has been developed to provide more detail by adding the process function, process characteristics and relevant metrics. Where suitable, the characteristics have been isolated so that they are analysed individually and as a whole to provide a deepened understanding of the interrelationships within the process. Using a matrix over a series of cause and effect diagrams delivers the benefits described in Section 2.5.3 of the literature review, allowing greater amounts of information to be contained, identifying the impacts of characteristics changes and inputs on successive operations and providing an ‘edit–friendly’ format. A tailorable Key allows symbols to be added and removed as necessary so that this tool has the flexibility required to be applied to any process.

Key
X - Characteristic created or changed by process parameter
R - Process parameter at one operation has a strong effect on product characteristic generated at another

				Process Characteristics									
				Operation									
				10		20			30		40		
				Clamp	Clamp Pressure	Drill	Drill Speed	Drill Feed Rate	Pressure	Insert Angle	Angle of Entry	Torque
Operation	**Process Function**	**Part Characteristic**	**Metric**	-	n/m^2	mm	RPM	m/s	n/m^2	deg	deg	Nm
10	Locate Item 1	Orientation	X,Y,Z	X	X							
		Position	mm	X	X							
20	Drill Hole	1 x M8 Hole	mm	R	R	X	X	X				
30	Locate Insert X	Insert X in M8 Hole	-				R	R	X	X		
40	Screw in Item 2	Item 1 and Item 2 Assembly	-						R	R	X	X

Figure 3-3 Example of an Enhanced Characteristics Matrix

In contrast to FMA, these tools are used in succession in order to provide information flow and a logical break down of the process. This is not to say that they cannot be developed iteratively, as the completion of one tool highlights a discrepancy with a previous one, but it must be appreciated that the Characteristic Matrix cannot be effectively completed without the structure and detail that is defined and developed through the preceding tools.

3.3.2 Step 2

In FMA the second step aims to identify failure modes and their effects. To achieve this, a Design FMEA is introduced. Despite numerous shortcomings associated with FMEA, the FMA approach ensures that the tool is used effectively by breaking down the acquisition of information over the previous tools. This prevents the analysis becoming overly laborious, subjective and cumbersome, but isn't so rigid as to be restrictive to thinking, such as with Advanced FMEA. With an inflow of system information from the first step used to establish the FMEA, the tool is then used as a 'living document' that manages the remainder of the analysis, with consequential efforts prioritised using the RPN.

Respectively, the second step of MFMA uses a Process FMEA to identify failure modes and their effects, with the intention of achieving the same benefits as FMA; supporting the tool without being over prescriptive. The contributing functions of the process have been segregated in Step 1 and can flow directly into the Process FMEA to populate the first column and are consequently used as the definition of the structure and scale of resolution for the analysis. Failure modes are then identified individually by comparing the required function with the four types of failure mode that are provided by the Ford Design Institute, as described in section 2.6.1 of the literature review. The effects of each of these failures on the rest of the process can subsequently be identified by analysing the downstream activities within the process, through examination of the Process Flow Diagram which catalogues the process and part characteristics and the Characteristic Matrix which shows the relationships and interdependencies that exist between them. The Severity of each of the effects is scored using an appropriate and consistent scale, which is used to prioritise the failure modes based on relative risk. Typically, a scale should be devised based on the nature of the process and the part under analysis, but due to the scope of this research the scale that is provided by the Automotive Industry Action Group (2008) is used. Despite circumventing best practice, this is sufficient for validating the effectiveness of the methodology as it only impacts its ability to prioritise action, rather than the sequencing of the tools or how MFMA achieves its fundamental aim.

Reaching beyond the objective of Step 2 in FMA, MFMA also identifies the causes of the individual failure modes at this stage. As the Characteristic Matrix is a tabulated form of a series of cause and effect diagrams, and is used to identify effects of failure modes on the remainder of the process, it stands to reason that it feasibly provides information relating to the causes of the failure modes. In this instance it requires examination of the process characteristics that influence how the part is transformed. It is appreciated at this stage that the Characteristic Matrix may not provide an in depth and fully conclusive description of the cause at a functional level, but is investigated further in Step 3. As the cause has been identified, the likelihood of occurrence can be scored.

Again, this will is achieved through the use of the Occurrence rating scale provided by the Automotive Industry Action Group (2008).

3.3.3 Step 3

In FMA, Step 3 aims to identify the cause of the failure mode by analysing noise factors, or sources of variation, that can exist in the system. This is a crucial element in improving robustness, as once noise factors are identified they can be prevented thereby reducing, or eradicating entirely, the occurrence of the failure mode through its cause, which is the objective of Step 4. FMA utilises P Diagrams and a Fault Tree in this step.

In MFMA, Step 3 operates slightly differently. The objective is to develop countermeasures to the failure modes through process improvements. However, this does involve developing a greater understanding of the causes of the failure modes, which have been provided in Step 2. At this stage, improvement and monitoring strategies like Six Sigma and process capability studies are applied to analyse and reduce the variation in the process and improve the robustness through countermeasure deployment. These strategies benefit from the scope and prioritisation provided by MFMA through the central Process FMEA, which has deconstructed the process into individual failure modes relevant to each operation. As a result, the weaknesses associated with these strategies, such as problem definition, project selection and scope creep, as described in the literature, can be mitigated. Outputs of these studies could include improved monitoring of process and part characteristics, so that trends can be monitored and consequently preventative action can be taken, such as with SPC, deployment of error proofing methods or Poka-Yoke devices, or process redesign if the risk is so large that such action is feasible, which would consequently require revisiting the previous MFMA steps as an iterative part of the design. Incidentally, as with FMA, there is always the option of doing nothing if risks are low enough to be disregarded.

The outputs of these efforts are inputted into the FMEA within the control columns, either as detective or preventative controls depending on their orientation. The likelihood of detection of each of the failure modes is then be rated using the Detection scale. On the other hand, if MFMA is being applied to

an existing process, or to a new process which is particularly similar to an existing process, there may be suitable controls currently in place. In this case, these are input into to the FMEA. At this point the full RPN is calculated to score the overall risk of the failure mode, based on the severity of its effects, the likelihood of its occurrence and the ability of the controls to detect or prevent the failure.

3.3.4 Step 4

The final step of the FMA framework aims to develop and verify countermeasures to failure. In this step, management strategies are established, verified and implemented into the design if proven successful. This is achieved through the application of a Robustness Worksheet which is used to assess the options for each of the noise factors and a Design Verification Plan which manages each of the studies. If proven effective, the required implementation or redesign to improve the system is entered into the FMEA under ‘Recommended Actions’.

In MFMA, the fourth step is also used to implement and verify the controls in place for reducing variation and is titled ‘Process Control and Validation’ accordingly. However, in this instance the countermeasures or, more specifically, process improvements have been designed in the previous step. The objective is achieved through the use of a Process Control Plan which, as suggested by the literature, is an effective method of implementing control measures, validating their effectiveness and ensuring the process output is in a state of control.

The Process Control Plan is presented as a table which provides a written description of the systems used to control the process. It is directly populated with information from the FMEA and improvement efforts, therefore continuing the flow of information through the MFMA process. As a result, this step makes sure that the outputs of the FMEA are effectively used, addressing one of the shortcomings associated with the tool. Furthermore, as the process is conducted the Process Control Plan should be reviewed regularly against the performance of the process. Any required improvements from these reviews are

entered in the FMEA under ‘Recommended Actions’ and the Process Control Plan updated for the implementation and continued validation.

The literature on FMA states that the relevant noise factor should be included as a measure in any study verifying the suitability of a countermeasure. The industry standard Process Control Plan abides by this suggestion, as the control methods are catalogued in relation to the process function and the part and process characteristics that are influenced at this step.

3.3.5 Summary

A manufacturing process based equivalent to FMA, named MFMA, has been devised, described and justified in relation to the literature. This method incorporates the distinguishing features of FMA that contribute to its success, which include high level steps with specific objectives, a dedicated tool set, clear and continued information flow between the tools and a functional approach to the analysis.

When viewing Figure 3-1 on page 54, it is clear that there has been some rearrangement of the objectives in Steps 2, 3 and 4 of the MFMA framework when compared to FMA. These are conscious changes, which have been made to redistribute the effort more evenly over the process. Identifying the cause of failure has been included in Step 2 of the MFMA framework, whereas in FMA this is conducted entirely in Step 3. The third step of the MFMA framework is used to develop the process improvement required, but this will include further investigation of the causes of failure modes where required, so this is not necessarily a radical change. In both FMA and MFMA the final step is used to verify the improvements and provide ongoing validation. In FMA this step is also used to develop the countermeasure. It is felt that due to the effort associated with these tasks, it would be better that they were contained within Step 3 of MFMA in order to prevent the final step from being overly laborious, which may compromise its effectiveness.

With the basis of the MFMA methodology established, a plan for validation of this method is required to demonstrate how effective this method is for identifying opportunities for process improvement and control, based on the principle of failure mode avoidance.

3.4 Validation Plan

3.4.1 Case Study as a Research Method

A case study is an empirical inquiry that investigates a contemporary phenomenon within its real life context (Yin, 1993). Anderson (1993) describes case studies as being concerned with how and why things happen, allowing the investigation of contextual realities and the differences between what was planned and what actually occurred. Furthermore, the strength of the case study is that it allows the researcher to gain a holistic view of a certain phenomenon or series of events (Gummesson, 1991). Consequently, as the MFMA framework has been designed to be used in industry, it is appropriate that the methodology is validated in this context in order to provide a realistic assessment of its performance and suitability in the field.

There is some criticism associated with the tendency of case study research to lead to generalisation, when the outcomes of a study are developed into all-encompassing blanket statements. The risk of this occurrence can be mitigated, firstly through appreciation of this fact when drawing conclusions from the study but also by conducting multiple case studies. Multiple case studies should be used to allow the opportunity for replication to occur as the development of consistent results can be considered more reliable (Noor, 2008). As a result, more than one case study will be used in order to further validate the MFMA framework and allow it to be applied in different manufacturing environments.

3.4.2 Case Study Plan

Although the MFMA framework was been designed with an emphasis on the development of new manufacturing processes, due to the length of time required to take a new process from the definition of its initial requirement to commencing in production, it was not feasible in the scope of this research to apply the MFMA framework to such a case. Consequently, the validation of the framework has been achieved through application of current manufacturing processes, using existing data to populate tools. However, this still demonstrates its effectiveness at improving robustness through the systematic identification of failure modes leading towards preventative action. Furthermore, increasing the opportunity for validation by applying the framework to existing

processes allows multiple case studies to be conducted which allows findings to be confirmed and consequently offer more reliable results.

As features of MFMA are pre-existing and are well documented in the literature, such as the Six Sigma methodology, they are not be the focus of this research. Consequently, the emphasis of this study is to develop and validate the MFMA framework.

The aim of this research, in reference to the MFMA methodology, was to answer the following questions;

1. Can the tools document complex manufacturing processes?
2. How effective is this method at developing a functional understanding of the process?
3. Is there a coherent flow between the tools and how well do they complement one another?
4. How effective is this method at facilitating the identification of failure modes, their causes and effects and provide opportunity for process improvement efforts?
5. How easy it is to deploy within the organisation?

These questions are answered through case study applications of the MFMA framework in the Company's manufacturing environments and subsequent discussion. The validation of the framework is achieved through the use of two case studies on differing manufacturing processes. This allowed the performance of the framework to be analysed in alternative environments and to determine its applicability as an overarching process to be used in the Company. Furthermore, this provided an opportunity to incorporate required improvements identified in the first case study. Although, this could have jeopardised the ability of the two case studies to offer the full benefits of replication in providing more reliable results, it was decided that two case studies that allow development of the framework was a more suitable aim.

3.4.2.1 Case Study 1

The first case study acts as a feasibility study of the framework and is used for initial verification of its suitability and effectiveness. As the success of the second half of the MFMA framework is reliant on the ability of the first half to functionally decompose the process, identify causal relationships and identify process failure modes in order to allow effective process improvements and ongoing control to be deployed, Steps 1 and 2 were the focus of the initial case study. Consequently, the second case study validates the process as a whole.

This case study was be on the machining of a metallic component. There are two reasons behind this. Firstly, this is a manufacturing process that is common in many areas of the Company and secondly there is clear visual transformation of the component throughout the process which assisted in the identification of part characteristics and therefore facilitates Process Mapping activities. This case study was conducted in isolation from the Company's employees in order to provide an initial test of the tools at capturing part and process characteristics from existing process documentation.

The aims wer to;

1. Apply the first two steps of the MFMA framework to a simple manufacturing process.
2. Test the suitability of the tools to capture process information.
3. Identify the strength of the flow of information between the tools and how this facilitates their completion and objective.
4. Assess the feasibility of the MFMA framework for providing scope for relevant improvement and control.
5. Identify areas of weakness of the MFMA framework that require improvement.

3.4.2.2 Case Study 2

The second case study validated the MFMA framework in its entirety, applying Steps 1 to 4, and incorporated any changes from the first application. Furthermore, during this study the MFMA framework was exposed to a team in order to validate it for use with the Company's employees.

This manufacturing process was on the heat treatment of rivets that are used for assembly manufacture. This process does not lead to a visual change of the component, but relies on the process to transform the microstructure of the components. Therefore, this provided an opportunity to demonstrate how MFMA can be applied to a process where failure modes may be less recognisable than in processes that result in visual transformation, which is true of the previous case study.

The aims were to;

1. Validate the full MFMA framework on a different process.
2. Complete the MFMA framework with the input of a team.
3. Incorporate any developments to the MFMA framework resulting from the first case study.
4. Demonstrate how the MFMA framework leads to process improvements and develop control plans, managed by the Process FMEA.

4 Case Study 1: MFMA Validation on a Machining Process

Elements of this case study have previously been presented and published by Goodland et al. (2013) under the title ‘Towards the Development of a Manufacturing Failure Mode Avoidance Framework for Aerospace Manufacturing’.

4.1 Introduction

The case study was conducted in the ‘Machining Facility’ of the Aerospace Company. This facility conducts machining of raw billets and castings of titanium, aluminium and stainless steel for a range of aircraft programmes. This facility is home to some of the most advanced machining capabilities, with machinery provided by Starrag, DST and Mazak, which are capable of machining to a tolerance of microns.

For this case study, the process that was been selected to assess the feasibility of the MFMA framework and validate its structure, internal objectives and tool set was that of the manufacture of a small stainless steel aircraft bracket. With assistance from staff within the facility, this process was selected due to its appropriateness for an initial application of the MFMA framework based on the following criteria;

- **Design** – The part consists of a variety of component features which will test the framework to identify and track throughout the process.
- **Size** – The finished component is of a scale suitable to view and examine.
- **Time scale** – This part is manufactured in a single day and therefore can be witnessed feasibly. Due to the size and complexity of some components manufactured in the facility, a single machining operation can run for well over 12 hours.
- **Rate** – These components are made regularly enough to allow the process to be witnessed on multiple occasions

The part is machined entirely in the Mazak cell on a Mazak FH - 6800, a two pallet horizontal machining centre. The cell is operated by five staff that,

although not directly involved in the completion of the case study, offers support, information and provides clarity throughout the process.

As the manufacturing operations of the Company are for the military and defence industry, photographs, drawings and part details are forbidden and have been omitted where necessary. However, this is not at the detriment of the study to validate the MFMA framework and toolset as ample detail is permitted in order to apply the tools.

4.2 Aims

The aim of this case study was to apply the MFMA framework to a simple manufacturing process in order to test its feasibility of identifying process failure modes and providing scope for improvement activity. Ultimately, the case study aims to assess the effectiveness of the tools, their sequencing and information flow and finally the ease at which potential failure modes are realised. Consequently, the requirements of this study were to complete the first two steps of the MFMA framework through the application of the proposed tool set;

1. **Boundary Diagram** – Scope the process
2. **Process Map** – Break the process down into key steps, mapping part characteristics
3. **Process Flow Diagram** – Identify the parameters that create part characteristics
4. **Characteristic Matrix** – Identify and understand the relationships between the part and the process
5. **Process FMEA** – Identify failure modes, their causes and effects and rate severity

By completing these documents, the strength of each of the tools, and the information flow between them can be examined.

4.3 Results

The tools were completed by witnessing the manufacture of the part, using the objective of the tools to focus the observations. Information was also provided by using existing process documents, such as part drawings, and through

regular, informal discussions with the cell operators. The MFMA framework assumes that all materials entering the process do so as specified, i.e. without pre-existing faults.

4.3.1 Step 1 – Process Functional Analysis

4.3.1.1 Boundary Diagram

Figure 4-1 shows the Boundary Diagram, which is used to capture the transformation of the part. In the context of the MFMA framework, the Boundary Diagram is intended to provide a graphical representation of the process being analysed and to scope the rest of the analysis. This is achieved by defining the process in terms of an input and an output at the highest level, describing the state of the part in measureable terms, identifying the internal interfaces that achieve this and the external interfaces which are influential to the process. Consequently, it is effectively a single functional block diagram, which is clearly illustrated in Figure 4-1.

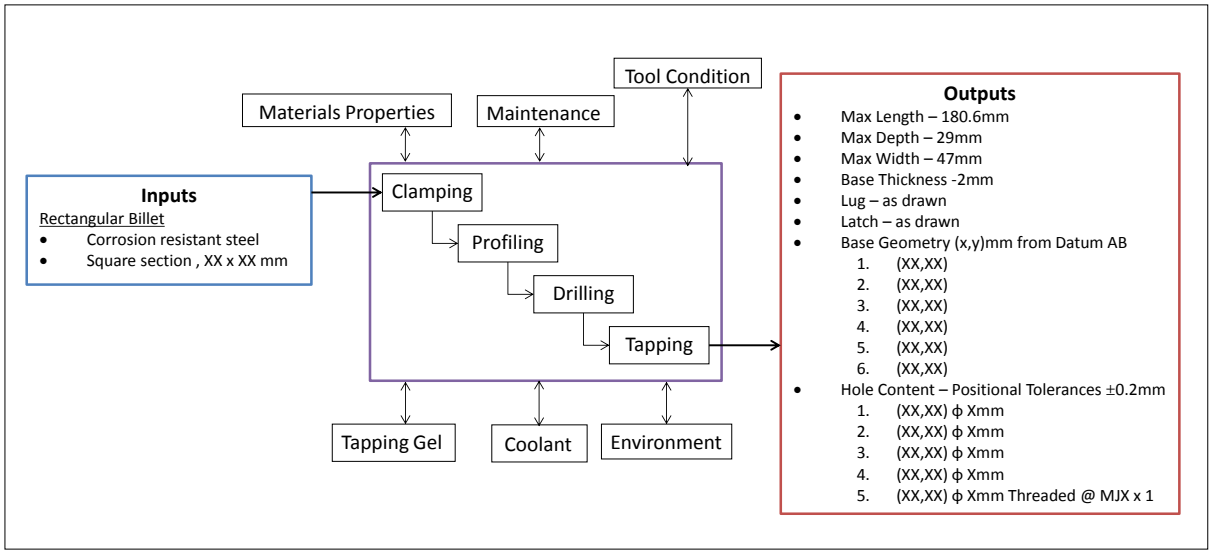


Figure 4-1 Boundary Diagram

Using material specifications, the input to the process has been detailed in terms of its physical state in terms of the billet material and its size. The length of the billet has not been recorded, as this was not detailed in existing documentation. Discussion with the operators confirmed that this is variable and as a result is not documented in the specification.

The output was described in terms of the features of the component that are created during the process. These are physical characteristics, and are described in terms of geometry, hole content, in regards to size and position, and features such as threads. These have been obtained using part drawings and the 'Condition of Supply' detailed by the customer, who in this case is internal, and are verified through a visual inspection of the part.

The internal interfaces provide an appreciation of the systems that are used within the process, in order to identify areas of focus for the analysis, but without detailing how and when the characteristics are achieved as this is not appropriate at this stage. Together they provide an overview of the transformation of the part within the process. The external interfaces demonstrate exchanges that can directly or indirectly affect the ability of the system to achieve its output and that may require investigation during the MFMA framework.

By documenting the process in this way, the requirement of the process has been deduced. With the input and output known, the boundary represents a transfer function. In order to understand this transfer function and identify how the part characteristics are created, the boundary is decomposed into a series of operations.

4.3.1.2 Process Map

Figure 4-2 demonstrates how the process defined using the Boundary Diagram was functionally deconstructed into a series of finite operations (the detail from the input and output boxes have been removed for appropriateness of presentation).

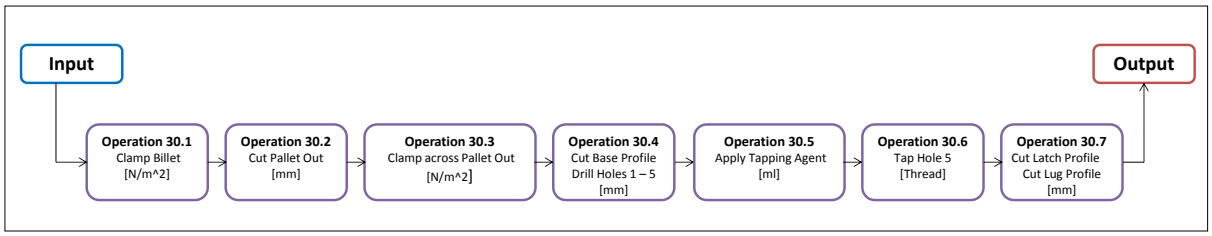


Figure 4-2 Functional Process Map

Using the Process Map, the principal process functions derived in the Boundary Diagram evolve into a sequence of activities, which can be deemed independent from each other due to transportation, operator intervention, change of tool and so forth.

A brief description is provided for each operation, which gives an appreciation of the state of the part after each of the process steps. As intended, a ‘Verb Object’ convention has been used as this supports the mapping exercise. The part characteristic, or transformation, that is created, altered or influenced during each operation has been recorded, along with its measurable.

Breaking the process down by this means provides a structure for the subsequent analysis, as the higher level process demonstrated in the Boundary Diagram is divided into manageable components, but which maintain association with one another as the output of a previous operation is the input to the next. The operations have been defined at a constant level and with a consistent numbering format which provides structure for the rest of the analysis.

With the process requirements captured in the Boundary Diagram providing a supportive inward flow of information, the Process Map maps these across succinct activities that contribute to the transfer function represented by the boundary, effectively breaking it down into a series of independent, but linked functions. Consequently, an understanding is gained of when and how each of the part characteristics is created, which is the first step in establishing a linkage between the part and process that allows the functional relationships to be understood and analysed.

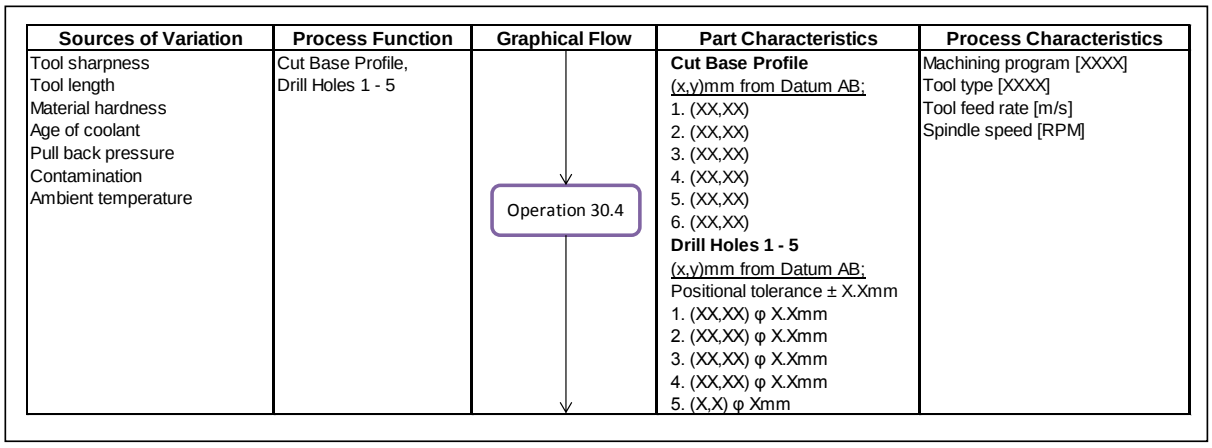
This tool was completed by ‘walking the process’ and identifying the key operations which are summarised by the Boundary Diagram.

4.3.1.3 Process Flow Diagram

The Process Flow Diagram is a more detailed expansion of the Process Map. The Process Flow Diagram takes the sequential structure of the Process Map and it’s descriptions of each of the steps and adds more technical information,

related specifically to that process step. This is demonstrated in the extract shown in Figure 4-3.

The sequence of operations, as compiled in the Process Map, is shown centrally within the document and in the column to the left the process function has been described. This information has flowed directly from the Process Map.



Sources of Variation	Process Function	Graphical Flow	Part Characteristics	Process Characteristics
Tool sharpness Tool length Material hardness Age of coolant Pull back pressure Contamination Ambient temperature	Cut Base Profile, Drill Holes 1 - 5	Operation 30.4	**Cut Base Profile** (x,y)mm from Datum AB; 1. (XX,XX) 2. (XX,XX) 3. (XX,XX) 4. (XX,XX) 5. (XX,XX) 6. (XX,XX) **Drill Holes 1 - 5** (x,y)mm from Datum AB; Positional tolerance ± X.Xmm 1. (XX,XX) φ X.Xmm 2. (XX,XX) φ X.Xmm 3. (XX,XX) φ X.Xmm 4. (XX,XX) φ X.Xmm 5. (X,X) φ Xmm	Machining program [XXXX] Tool type [XXXX] Tool feed rate [m/s] Spindle speed [RPM]

Figure 4-3 Process Flow Diagram

On the right hand side of the table the part and process characteristics are shown. The part characteristics relate to the physical state of the part and are completed using the existing information flowing inwardly from the Boundary Diagram. The process characteristics are measurable inputs of the process that are used to create the part characteristics and represent the parameters which are influential and that can be actively controlled by the process.

On the extreme left of the table, the sources of variation, or ‘noise factors’, for each of the process steps are recorded. These are interfaces that are influential on the outcome of part characteristics but generally cannot be easily controlled, i.e. they vary but are difficult to monitor or change at will. These are identified using the external interfaces documented on the Boundary Diagram.

The format of this document means that the additional information is documented against each process operation, which is beneficial as it develops a relationship between part and process characteristics, which was founded in the Process Map. By breaking these activities down over a number of complimentary tools the integrity of data is not compromised; the information is manageable and thorough. This document provides the scope and level of

resolution for the Process FMEA as it details separate operations, their functional requirement and the causal relationships which led to the requirement being achieved or compromised.

4.3.1.4 Characteristic Matrix

As the Process Flow Diagram has collected detailed information about the part and process characteristics, illustrating the requirements of the process, a Characteristic Matrix can be produced to identify the what, how and when. Figure 4-4 shows an extract of this document.

Key
X - Characteristic created or changed by process parameter
C - Characteristic used for clamping
L - Characteristic used for location
R - Process parameter at one operation has a strong effect on product characteristic generated at another

				Process Characteristics																													
				Operation																													
				30.1	30.2				30.3	30.4				30.5		30.6				30.7				40.1	40.2								
				Clamp Pressue	Machining Program	Tool Type(s)	Tool feedrate	Spindle Speed	Clamp Pressue	Machining Program	Tool Type(s)	Tool feedrate	Spindle Speed	Type of tapping gel	Quantity of tapping gel	Tap (Tool) Type	Tapping Depth	Tool feedrate	Spindle Speed	Tool Type(s)	Tool feedrate	Spindle Speed	Deburring tool	Clamping Pressure									
Operation	**Process Function**	**Part Characteristic**	**Metric**	n/m^2	XXXXXXX	XXXXXXX	m/s	RPM	n/m^2	XXXXXXX	XXXXXXX	m/s	RPM	XXXXXXX	ml	XXXXXXX	mm	m/s	RPM	XXXXXXX	m/s	RPM	XXXXXXX	n/m^2									
30.4	Cut Base Profile, Drill Holes 1 - 5	**Cut Base Profile, (x,y)mm from Datum AB;** 1. (XX,XX) 2. (XX,XX) 3. (XX,XX) 4. (XX,XX) 5. (XX,XX) 6. (XX,XX)	[mm] (x,y)		**R**	**R**	**R**	**R**	**R**	**X**	**X**	**X**	**X**											**CL**									
		Drill Holes 1 - 5, (x,y)mm from Datum AB; 1. (XX,XX) φ X.Xmm 2. (XX,XX) φ X.Xmm 3. (XX,XX) φ X.Xmm 4. (XX,XX) φ X.Xmm 5. (XX,XX) φ Xmm	Position - [mm (x,y)] Diameter - [mm]		**R**	**R**	**R**	**R**	**R**	**X**	**X**	**X**	**X**			**X**	**X**	**X**	**X**														

Figure 4-4 Characteristic Matrix

As shown, the critical process parameters have been listed along the horizontal axis of the matrix, categorised by the operation in which they occur. Along the vertical axis, the part characteristics are listed, as determined in the Process Flow Diagram, and are formatted according to the operation in which they are created. The function of the operation is stated and, as with the process parameters, the metric by which they are measured is given. Again, the structure of this document is designed to easily incorporate the information generated in the previous documents, allowing for efficient completion.

The Characteristic Matrix is used to identify and characterise the nature of the cause and effect relationships and interfaces between the part and the process.

To do this, a Key was developed in order to represent the nature of the different relationships existing in the process under examination. Through the creation and use of a tabulated form of the process, all relationships can be systematically and independently considered which enables a comprehensive understanding of the mechanisms of the process, by documenting specifically how and when characteristics influence each other throughout its entirety.

For instance, as the extract in Figure 4-4 shows, the part characteristics created in operation 30.4 are used for clamping and location in operation 40.2. As a result, it has been identified that the process characteristics applied during operation 30.4 have a significant effect on the ability of operation 40.2 to achieve its function and thus demonstrates interdependency. A linkage is also identified between operations 30.4 and 30.6 as holes drilled in the former are tapped in the latter, demonstrating another linkage not only between the part and process but from one operation to another.

Consequently, this Characteristic Matrix is an information rich document and the data it contains provides a strong foundation for the identification of potential failure modes as it highlights dependencies between the parts and process, which aids in identifying the effects, or causes, of process failures on subsequent, or respectively preceding, operations. The Characteristic Matrix has also effectively maintained the scope of the analysis that was defined from the Boundary Diagram and is intended to be preserved throughout the MFMA framework.

4.3.2 Step 2 – Process Failure Mode Identification

Once a detailed, functional understanding has been developed in Step 1, including the process requirements, the operations used to achieve them and the interdependent relationships that the process relies on, process failure modes were systematically identified and examined in Step 2 using a Process FMEA.

4.3.2.1 Process FMEA

The Process FMEA identifies potential modes of failure within the manufacturing process, by focussing on the intended function of each step of

the process, and the likely effect these failures will have on the part characteristics.

During this step the aim is to complete the left hand side of the document, which outlines the mechanism of failure and will be utilised in Step 3 to provide scope for improvement action.

Figure 4-5 shows these components of the Process FMEA and how their completion is supported by information flow from the previous tools.

The ‘Process Function’ and ‘Process Requirement’ columns were populated directly by information from the Characteristic Matrix, which was first documented in the Boundary Diagram and then developed upon in the Process Map and Process Flow Diagram. Through the comprehensive understanding of the process achieved by these tools, failure modes were identified with reference to the four types of failure mode as listed in Section 2.6.1.

The effects of the failure mode on the rest of the process is then examined, this is achieved through the support of the Characteristic Matrix. As illustrated in

Figure 4-5, by following the rows associated with this process function and its part characteristics, instances where these features interface with other aspects of the process can be observed conveniently. In this case, these features are used for a clamping and location operation in the next stage of the process.

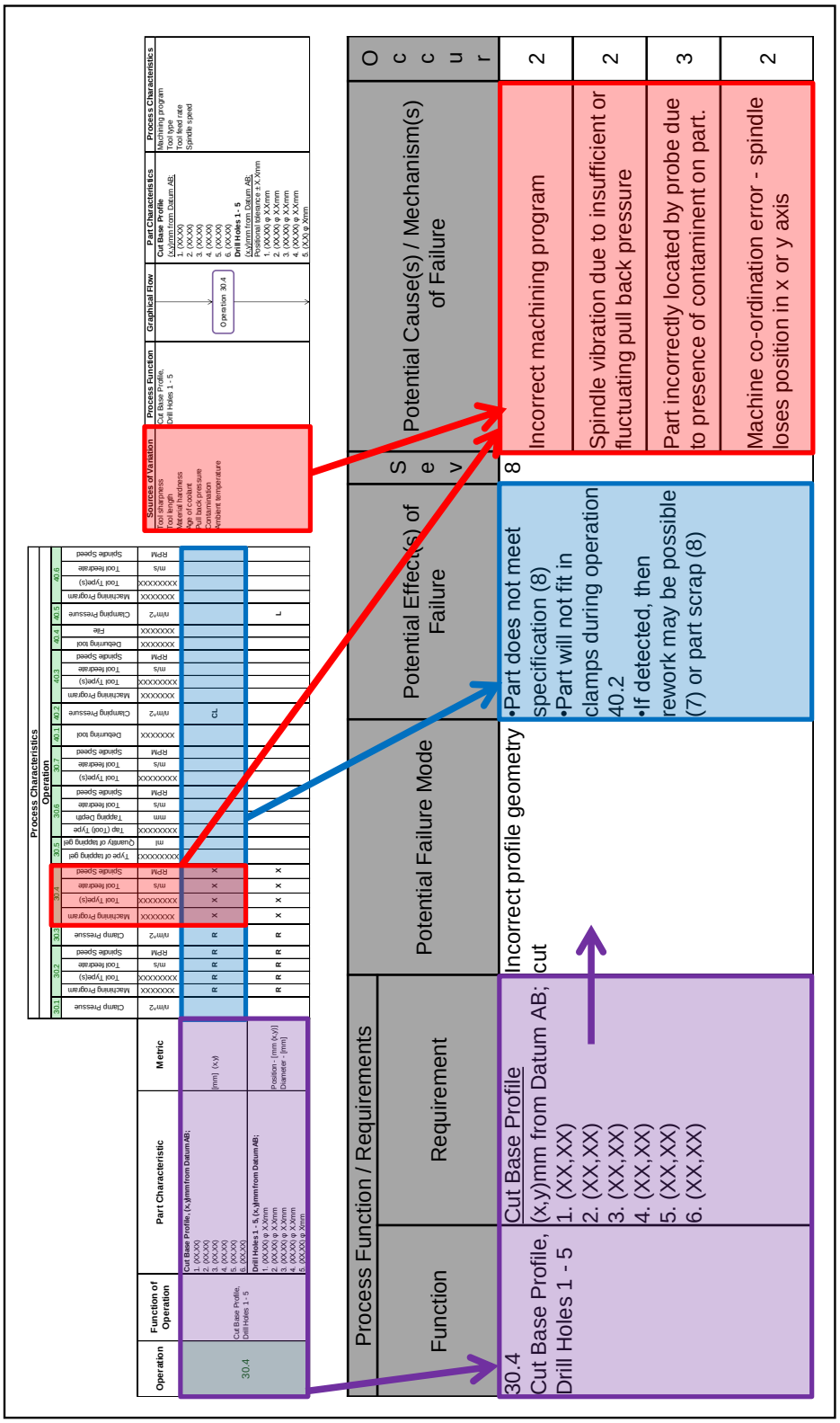


Figure 4-5 Process FMEA

The Severity of each of the effects of failure was rated using the scale provided by the Automotive Industry Action Group and the most severe outcome documented in the ‘Severity’ column. As previously discussed, there is an opportunity to develop tailorable criteria, or a selection of various criteria for different processes, but this is not a priority at this time.

The potential causes of failure were identified using the Characteristic Matrix, but also the sources of variation that are contained in the Process Flow Diagram. Examining which process characteristics are influential on the part characteristics, denoted by a symbol at their intersection on the Characteristic Matrix, was effective at providing a means to identify the causal relationship between the process and the part and subsequently the causes of the failure. The sources of variation provide external causal factors, that are not directly engineered within the process but influence its outcome. Step 3 of the MFMA framework would then take the problem statement provided by the failure mode, its effects and causes and use it to scope further investigation and countermeasure development. As with the effects of failure, and as is customary, the likelihood of the occurrence of each of the cause of failure modes is recorded using the standardised criterion.

4.4 Discussion

The Boundary Diagram is effective at determining the beginning and the end of the process that is the focus of the MFMA study, achieved by defining the part’s state at these instances. However, in this case study it is clear that only the geometric features of the part have been captured. Although these describe the main transformational requirements of the process, it does not allow for the fact that other failure modes may exist. For instance, the process could fail by misidentifying the part or not transporting the part into the correct location after processing.

This tool is also used to initially identify the internal and external interfaces. The internal interfaces are easier to identify, as they are based upon what needs to happen in order to meet the requirements, whereas acknowledgement of the external interfaces is susceptible to brainstorming, rather than a structured method of identification. Regardless of these weaknesses, the Boundary

Diagram does effectively capture the manufacturing process at the highest level, which is essential for functional decomposition.

The Process Map is successful in deconstructing the process in order to identify when each of the part characteristics is created. However, as it was conducted on just one level, it could be argued that it is too 'one dimensional' and fails to capture processes that occur within each of the process steps it defines. For example, in Operation 30.4 the profile is cut and the holes are drilled, which results in the largest physical transformation of the part at any one point, but this is too broad a function in order to fully identify process failure modes for control. Many mechanisms and interfaces will exist within this process, which are in danger of being overlooked when the process is mapped at this level. For example, the order that holes are drilled could prove to be influential to the reliability of the process. This factor would impact how much time the tool has to cool between drilling operations, which could affect the accuracy of the tool based on thermal expansion that occurs as a result of drilling the previous hole and therefore affect the accuracy of the subsequently drilled hole. Consequently, although the Process Map describes the operations that create the part characteristics, improvements could be made to the tool to describe and clarify each of the part characteristics after each operation in order to better understand how they are being altered throughout the process.

The strength of the Process Flow Diagram is how it summarises all the process information succinctly and in reference to each step; in order to complete this document the process needs to be well understood. However, as the tools are linked together in order to allow information flow, the Process Flow Diagram is restricted to the level of detail captured in the Process Map, which as discussed is potentially insufficient. The identification and addition of process characteristics and sources of variation are supported by looking at each operation in isolation and what creates and compromises its requirement, but at this level of detail there is potentially too much detachment to allow all the information to be uncovered systematically.

Completing the Characteristics Matrix is a very effective exercise for identifying part to process and process to process linkages and therefore deriving a deeper

understanding of how the process achieves its function and which interfaces are present. As a result, it is a crucial prerequisite to the Process FMEA by providing a logical table of what the potential causes and effects of failure modes can be. Furthermore, the format and structure of the information is more suitable and user friendly in comparison to a series of cause and effect diagrams. However, the incoming data from the previous tools has prescribed a level of examination that is perhaps not detailed enough to correctly identify all functional failures modes. This is illustrated in the Process FMEA, where the failure mode ‘Incorrect profile geometry cut’ is perhaps too vague in relation to the machining of the part’s geometry.

The Process FMEA successfully pulls the functional understanding developed through the use of the previous tool set together in order to identify the failure modes that could potentially occur during the process operation. How the structure of the document is created, based on a functional description and deconstruction of the process, and the efficiency with which this tool can resultantly be completed is undeniable when compared to completing an FMEA study without the completion of supportive tools.

Identifying the effects of failure through the use of the Characteristic Matrix is robust, but the ability of this method to uncover the causes of failure, especially when it is considered these are intended to provide specific improvement or control measures towards the required creation of part characteristics, demonstrates weakness.

For instance, the causes identified on the Process FMEA are at differing levels of what can be engineered within the process. Incorrect selection of the machining program is a valid cause of a failure and is directly associated with incorrect geometrical output, but unacceptable spindle vibration due to insufficient pull back pressure, although a potential cause of incorrect geometry and a source of variation, as correctly identified, is just one of many causes that would affect the machinery’s capability to achieve the required geometric tolerance. The issue present is that the FMEA has captured causes at both an operational level, in terms of the machining program selection, and at a process capability level, leading towards machinery level. Even discounting the fact that

pull back pressure is only one of a variety of different potential causes of spindle vibration, it should be acknowledged that to remain at a consistent level of analysis, the cause should be ‘Insufficient machine capability’. This could then provide scope for an investigation of the machine’s capability in regard to machining the correct geometry required for this part. However, it should be realised that this is a failure mode at a lower process hierarchical level and prompt subsequent investigation at an appropriate level of detail. It therefore stands to reason that further functional decomposition is required in order to appreciate the operation of the process on different levels, which begins at the Process Mapping stage, in order to allow control efforts to be appropriately scoped.

In terms of the structure of the MFMA framework, the case study has confirmed that the sequence of the tools is appropriate and logical, beginning by defining what the process is intended to achieve, then how it will achieve it and the influences and interrelationships between the part and the process which then provide the foundation of how the process could fail and by what means.

The flow of information between the tools is strong and clearly visible. This demonstrates the integration between the tool set, which consequently facilitates effective and efficient completion. This is proven by the fact that none of the tools, other than the initial Boundary Diagram, are compiled from a blank template as the structure and initial information is provided from previous exercises. This leads to the understanding of the process evolving throughout the MFMA process. The scale of the tools is manageable, as the information used to build the tools flows in a logical and structured manner which largely mitigates the need for brainstorming activities which can be disordered, prove subjective and cause the scope to wander.

4.5 Learning Outcomes

In conclusion, the case study has been successful as an initial implementation of the MFMA framework. It has demonstrated that the tools are in an appropriate sequence, are capable of capturing process information effectively and that a clear flow of information exists between them that allows them to be completed efficiently.

However, it is found that identifying external interfaces and sources of variation are areas of weakness in the framework and require additional support.

Furthermore, it has been discovered that a decomposition of the process at one level is not appropriate for correctly identifying the cause of process failure modes as it does not provide enough detail to understand the mechanisms of failure systematically or consistently. This has been identified as originating from the Process Map and has had a detrimental effect on the ability of the tools downstream to maximise their potential.

4.6 Developments of the MFMA Framework

Prior to the second case study implementation of the MFMA Framework, opportunities were identified to address the weaknesses in the framework that were uncovered during the first implementation.

The Boundary Diagram was developed to capture additional information beyond the geometric characteristics of the part, by including characteristics of the parts state such as location, material specification and quantity as these factors are relevant towards the use of the MFMA framework in a production environment and also allows additional process failures to be captured. Also, differentiation between external and internal interfaces is achieved by defining external interfaces as ‘any input into the process that is not directly applied to transform the part’ which is considered in terms of people, parts, process and plant.

In order to address issues associated with mapping the process on one level, which consequently impacted the depth of analysis in the rest of the MFMA framework, the Process Mapping stage will be conducted through iterative decomposition through levels of the process. Furthermore, each of the part characteristics identified on the Boundary Diagram will be stated after each stage of the process to prompt analysis regarding how and when they are changed.

Rigour will be applied to the identification of sources of variation during the completion of the Process Flow Diagram by supplementing the activity with a P Diagram. This aims to provide an opportunity where each of the process steps and their function can be analysed in isolation, removed from the influence of

the rest of the process. It is also felt that identifying the different error states of the process outputs will also aid in the identification of failure modes and be a valuable input to the Process FMEA.

For clarity, Figure 4-6 illustrates the proposed changes to the MFMA framework that will be implemented and validated through the second case study, with additional tools highlighted in red and tools which require development highlighted in blue.

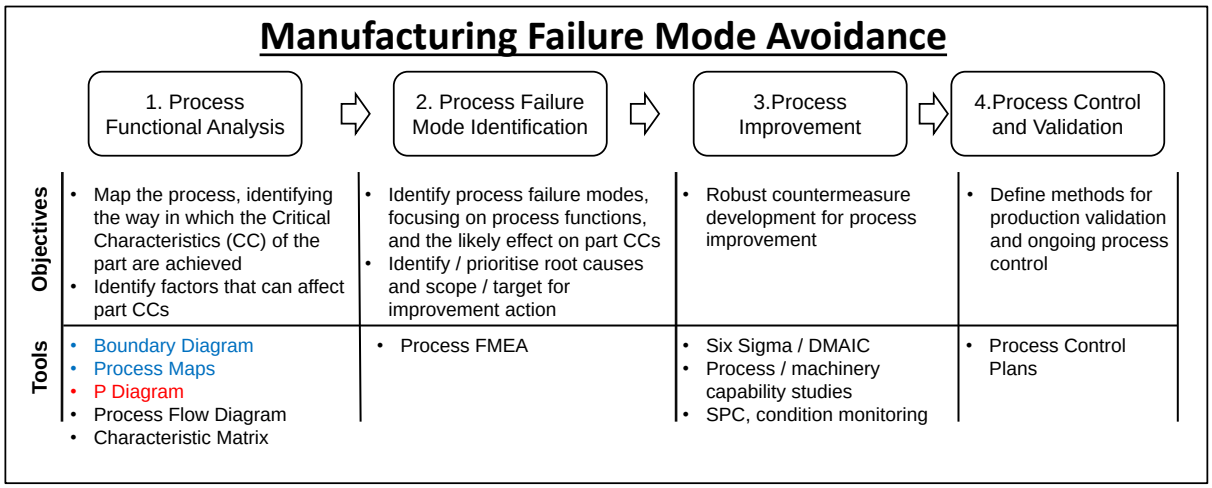


Figure 4-6 Developments to the MFMA Framework

5 Case Study 2: Deployment of MFMA on a Heat Treatment Process

Elements of this case study have previously been presented and published by Goodland et al., (2013[b]) under the title 'A Manufacturing Failure Mode Avoidance Framework for Aerospace Manufacturing'.

5.1 Introduction

The second case study was conducted in a small production facility which has capabilities that include machining, treatments, non-destructive and destructive testing and material treatment.

The process that was selected for this study is for the heat treatment of aluminium rivets that are used for the assembly of products for a variety of aerospace programmes. This process aims to reduce the hardness of rivets that are procured from an external supplier in order to improve workability during riveting operations. This transformation is achieved by altering the microstructure of the material by heating them in batches and then quenching them in coolant, after which they are dried and stored in a freezer in order to prevent the rivets from hardening through natural aging.

This process was selected to test the MFMA framework based on the following criteria;

- **Transformation** – The part characteristics are not as immediately identifiable as those in the first case study as the transformation is to the microstructure of the material. This will validate the framework for application on different process to the first case study.
- **Time** – This process is conducted in a single day which facilitates the study by allowing it to be witnessed easily and facilitating team involvement
- **Team Availability** – A small team of employees associated with the process have been made available to conduct the MFMA framework

Due to the sensitivity of the Company, technical data has been removed where necessary, but not to a degree which impacts on the ability of the case study to demonstrate validity of the MFMA framework.

5.2 Aims

The aims of this case study were to;

1. Validate the full MFMA framework on a different process, identifying information flow in Steps 3 and 4
2. Complete the MFMA framework with the input of a team
3. Incorporate developments to the MFMA framework resulting from the first case study
4. Demonstrate how the MFMA framework leads to process improvements and develop Control Plans, managed by the Process FMEA.

5.3 MFMA Team

A team for this case study implementation was formed to conduct the analysis. The team members were selected from employees of the production team located in the facility to ensure that they possessed the required knowledge and would have familiarity with the process. Individuals were also chosen based on their role within the business which would best allow for a cross functional team.

The following roles were selected;

- Research Engineer
- Production Manager
- Team Leader Production
- Supply Chain
- Treatment Supervisor
- Mechanical Engineer x 2
- Heat Treatment Operator x 2
- Business Support
- Metallurgy
- Mechanical Test

The MFMA framework was conducted through the use of regular group meetings, lasting between 1 and 2 hours. The objective of each meeting was focussed around the tool sets that combine to form the MFMA framework.

To engage with the team an initial meeting was held in order to give context to the study. The aims of the case study were explained from a research perspective, the MFMA framework, its higher level process steps and their objectives were described and the tools that are applied were illustrated using the outputs of the first case study.

5.4 Results

The results are presented using extracts of the tools completed during the study, with a description of modifications from the first case study provided along with observations of the team influence on their completion.

5.4.1 Step 1 – Process Functional Analysis

5.4.1.1 Boundary Diagram

Figure 5-1 illustrates the Boundary Diagram produced in this study. The Boundary Diagram operated in a similar sense as it did in the first case study, using a single block diagram to define the process as an input and an output, described in terms of measurable characteristics, either side of the process and isolating it for the rest of the framework.

Based on the findings of the first MFMA implementation, the inputs and outputs of the process have been expanded to include more facets than just the geometric characteristics. This was appropriate, as it would have proven very difficult to define the changes that result from this process based purely on these characteristics, as there is no required change geometrically. These additions included location, part number, number (quantity), temperature, and mechanical properties such as hardness and tensile strength.

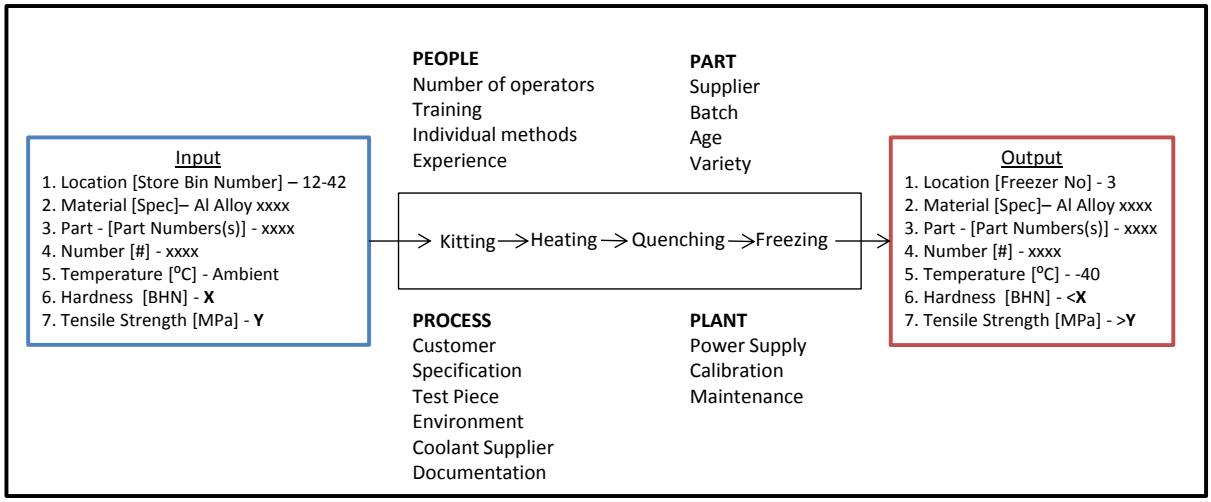


Figure 5-1 Boundary Diagram

Furthermore, the external interfaces have been structured under four categories, which are People, Part, Process and Plant and are identified on the basis that they are non-direct inputs to the process, or rather inputs to the process that are not directly applied towards the transformation of the part.

This tool was completed by the team in a one hour session. With reference to the Boundary Diagram from the first case study, and facilitation from the author, part characteristics were identified logically and once defined changes in these factors were straightforward to uncover, when related to the function of the process. In order to do this the team first discussed the overall requirement of the process, led by the mechanical engineers and the operators, to ensure a universal understanding was possessed. Part characteristics were identified independently as either an input or an output, depending on how they relate to the process, but then added to the other to ensure consistency. For instance, temperature was identified as a requirement of the process to achieve and was then subsequently added as an input. The team also decided to number the characteristics so that they could be easily referenced.

It was felt that by categorising external inputs the team was better enabled to identify them. This prompted discussion as initially machinery and tooling, such as the furnace and the loading tray, were identified as external causes but then it was resolved that these were used to directly transform the parts in terms of temperature and location respectively. The internal interfaces were identified on an informal basis by considering how the process operated.

5.4.1.2 Process Mapping

In order to address the issues that were exposed in the first case study, related to mixed level of functional detail leading towards inconsistent identification of failure modes and causality, the functional decomposition from the Boundary Diagram was conducted through operational levels, as shown in the figure below.

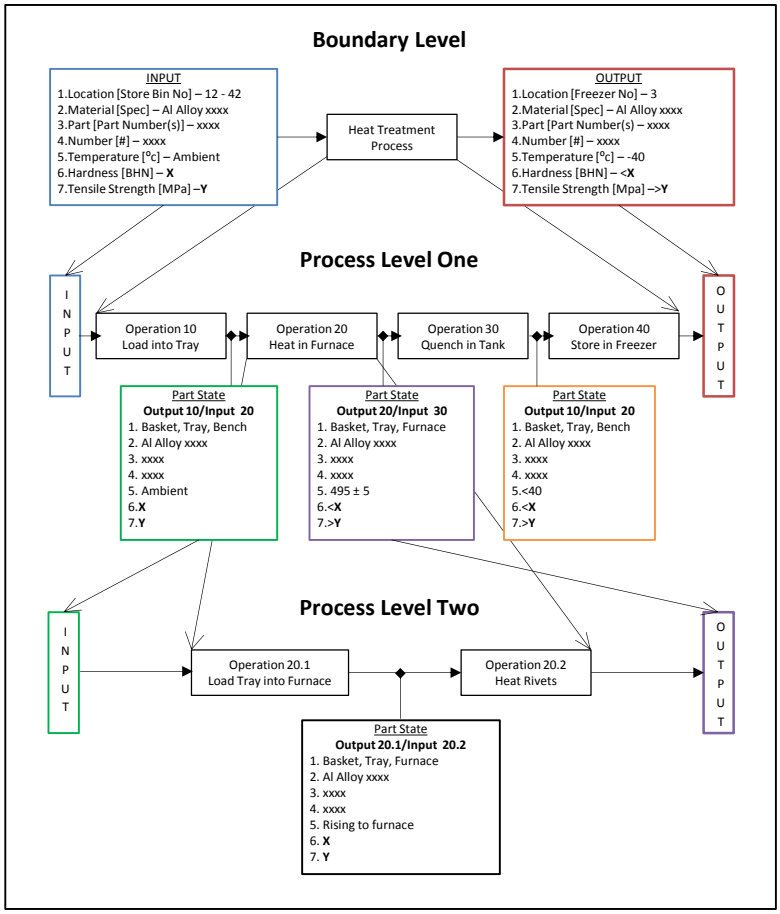


Figure 5-2 Enhanced Process Mapping

The first level of mapping described the operations that occur in order to create the desired output characteristics. At this level, the part states were defined in relation to observable instants between operations, which demonstrate exactly how and when each of the part characteristics are created or changed. This is shown in Figure 5-2, by using nodes in between each of the operations that denote functions of the process. This approach was closer to the technique used in FMA when the System State Flow Diagram is applied. It was also documented that the output of one operation is the input of the subsequent operation.

The decomposition was continued iteratively to subsequent levels of detail of the process, for each of the operations. This enabled deeper comprehension of how the process achieves its requirements through an understanding of the functional logic within each of the process steps. This was conducted with stricter adherence to the literature on functional decomposition. Again, by recording the part characteristics between each of the operations, changes were identified that may have been overlooked had the mapping only been conducted at one level as it was in the first case study. Also, the state of a part characteristic was recorded even if it remained unchanged. Consequently, a richer appreciation of the transformation of the part was developed.

These maps were created through a series of one hour meetings with the team. Initially, the level one map was produced in a single meeting. The team found it straightforward to break the process down into distinct operations, due to the boundary and internal interfaces defined previously. With significant input from the process operators, the high level operations were determined on the basis of significant transformation of the part using machinery or equipment. For consistency, the team decided to determine the boundary between each of these operations by using transportation (including loading or removal) of the parts as separation point. Once the operations and their sequence were defined, part characteristic states were documented at each step to identify how and when they were changed and were recorded using the same numbering sequence as founded in Boundary Diagram. As a result, each of the part characteristics was defined at each step of the process, even if it is unchanged.

Each of the level two Process Maps was completed in subsequent one hour meetings, using the level one map as a guide. These were done in the same manner as the higher level, with each of the operations viewed as a Boundary Diagram to be expanded for higher resolution. Once all of the maps were completed, each of the operations was numbered to provide for numerical identification.

5.4.1.3 P – Diagram

Another addition to the MFMA framework was the P Diagram. Figure 5-3 shows an example from Operation 20.2. This tool was introduced to support

identification of the sources of variation and the control required at each process step, after it was found that there was a lack of structure in the previous implementation.

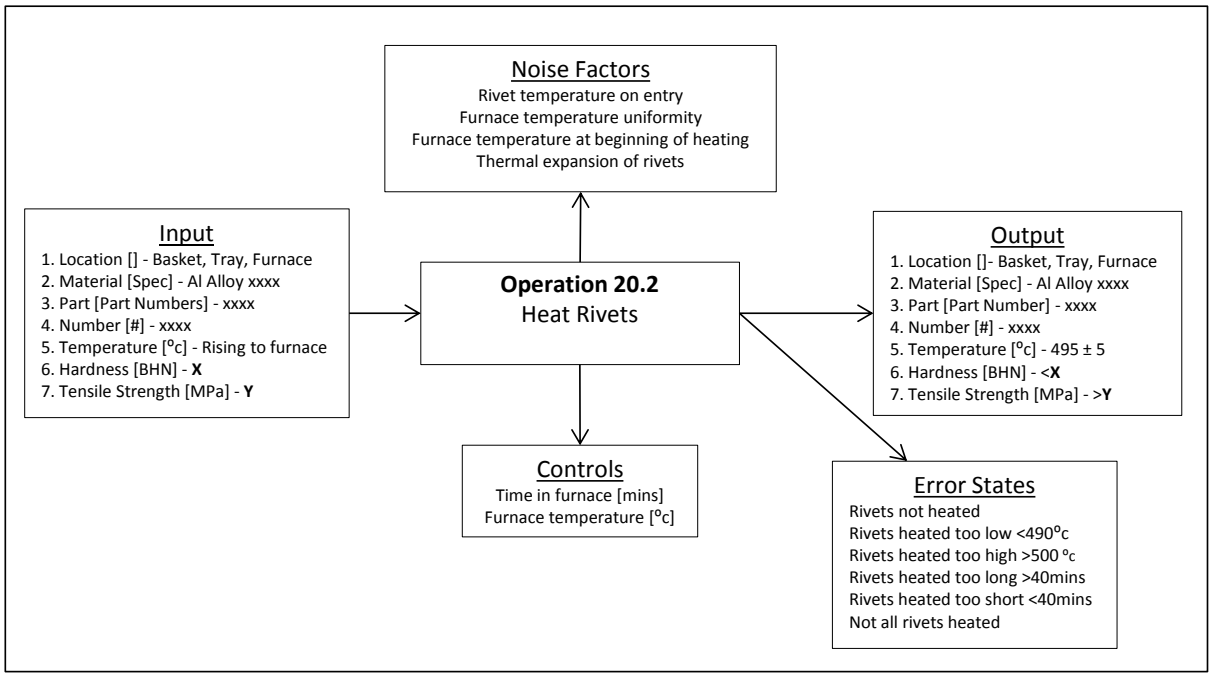


Figure 5-3 P Diagram

The process step and its boundary were directly imported from the Process Maps. Firstly, by considering the outcomes of the process that were alternative to those previously defined in the required outputs, the team were able to identify the 'Error States' of the process function. Controls that are used to achieve the process requirements are recorded along with the factors that are potentially variable, which are known as 'Noise Factors'.

This represents the first linkage between the part and the process, as after defining the required part characteristic, the error states are related to process requirements that are achieved by controls and compromised by the noise factors within the process.

The team found some aspects of the P Diagrams challenging to complete. Identifying error states was straight forward, as it was supported by the part characteristic required and therefore uncovering how the process would fail to achieve this was natural. However, confusion occurred when differentiating

between controls and noise factors. The team frequently added process factors that should be controlled in each process step rather than what was capable. As a result, sources of variation were regularly mislabelled as controls. It was agreed that, consistent with the definitions in Section 2.2, control factors would relate to what the engineer can actively control during the process step and that noise factors would be defined as variations that couldn't be controlled by the engineer within the step and that would comprise the process to achieve its requirement.

5.4.1.4 Process Flow Diagram

Figure 5-4 shows how the addition of P Diagram supports the information flow which underpins the MFMA framework and provides the structure for the Process Flow Diagram as the Process Map did in the previous case study.

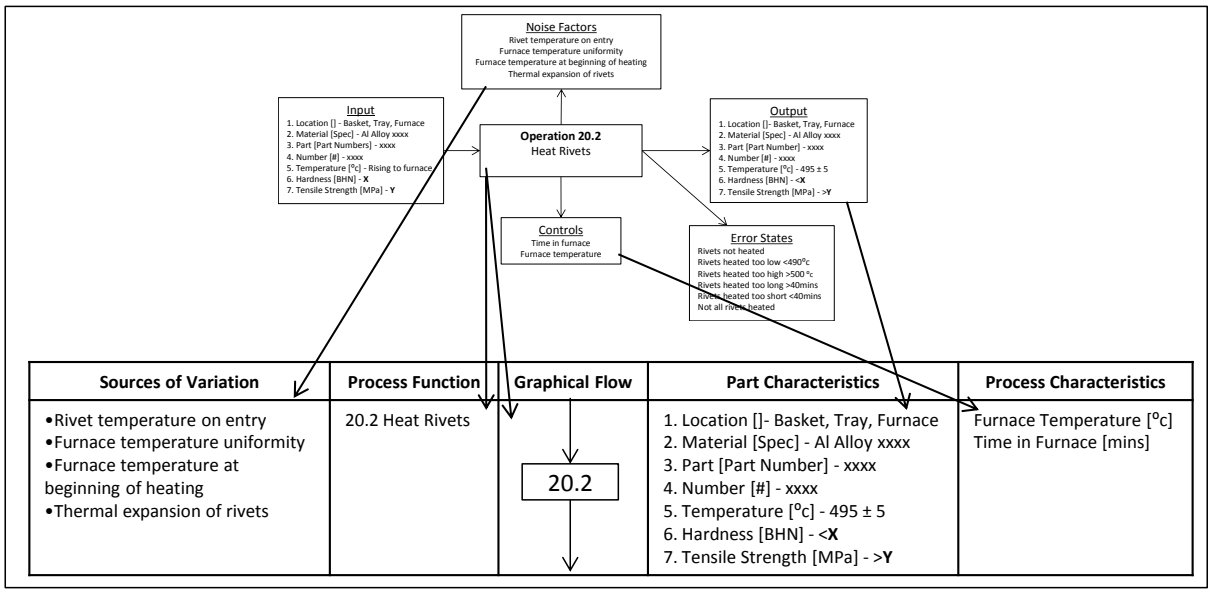


Figure 5-4 Process Flow Diagram and information flow from P Diagram

The process function and graphical flow was unchanged from the Process Map, as are the part characteristics, with the difference in this implementation being that all characteristics are recorded rather than only those that are created or changed in the specific operation. The sources of variation were directly inputted from the noise factors identified using the P Diagram, with the benefit of considering the error states that could be outputted from the process. The process characteristics, which are the inputs used to transform the part and meet the process requirements, were added to the Process Flow Diagram with

an input from the P Diagram also. In this extract, as is often the case, they are the same as the controls but often additional inputs are identified that create part characteristics.

Further supported by these additional inputs, the Process Flow Diagram operated in the same manner as before, by promoting a detailed expansion of the Process Map and adding specific technical information to each of the operations in an all up table format at the level of resolution defined in the functional decomposition.

This document was completed by the team through two, one hour meetings. The support of the P Diagram and the previous tools was beneficial for the creation of this table as the inward information flow was very strong and ensured that large aspects of the tool were populated by default. However, the team still took the time to review this information with the process documented in totality at this level, to check for consistency and appropriateness of information. Process characteristics were added where necessary, when they weren't identified as controls on the P Diagram.

5.4.1.5 Characteristics Matrix

The Characteristics Matrix, which proved effective at identifying part to process linkages in the first case study, remained largely unchanged in structure other than including all of the part characteristics, which have been tracked consistently through both the process and the MFMA framework, as shown in Figure 5-5.

The team found this tool and its population to be a worthwhile exercise as it uncovered relationships between the process that were present but not intentional and therefore lead to a greater understanding of the subtler interfaces. However, it was found to be costly, taking a lot of time to complete, and confusing due to the scale of the matrix (only a small extract is shown). The strategy that the team employed was to work through the matrix diagonally, identifying the relationships that were intended and then assessing the impacts these had on the rest of the process, both in terms of part characteristics on the vertical axes and process characteristics on the horizontal axes. This approach

encouraged consideration of potential failure mode causes and effects which is crucial for the next step in the MFMA framework. This tool required four, one hour sessions for completion.

Sources of Variation	Process Function	Graphical Flow	Part Characteristics	Process Characteristics
•Rivet temperature on entry •Furnace temperature uniformity •Furnace temperature at beginning of heating •Thermal expansion of rivets	20.2 Heat Rivets	20.2	1. Location []- Basket, Tray, Furnace 2. Material [Spec] - Al Alloy xxxx 3. Part [Part Number] - xxxx 4. Number [#] - xxxx 5. Temperature [°c] - 495 ± 5 6. Hardness [BHN] - **<X** 7. Tensile Strength [MPa] - **>Y**	Furnace Temperature [°c] Time in Furnace [mins]

				Key Process Characteristics															
				Operation															
				10.1		10.2			10.3			20.1					20.2		
				Operator	Ambient tempearure	Operator	Ambient tempearure	Number of rivets per basket	Operator	Ambient tempearure	Distribution of rivets in tray	Operator	Tray position	Furnance temperature	Rate of heating	Time in furnace prior to heat treatment	Furnace temperature	Time in furnace
Function of Operation	**Part Characteristic**	**Part State**	**Metric**	[-]	[°C]	[-]	[°C]	[#]	[-]	[°C]	[-]	[-]	[-]	[°C]	[°C/min]	[min]	[°C]	[min]
20.1 Load tray into furnace	Location	Baskets, Tray, Furnace	[-]									**X**						
	Material	Al Alloy xxxx	[Spec]												**R**			
	Part	xxxx	[Part Number]	**R**														
	Number	xxxx	[#]	**R**														
	Temperature	Rising to Furnace Temp	[°C]								**R**		**X**	**X**	**X**	**X**		
	Hardness	**X**	[BHN]										**X**	**X**	**X**	**X**		
	Tensile Strength	**Y**	[MPa]										**X**	**X**	**X**	**X**		
20.2 Heat rivets	Location	Baskets, Tray, Furnace	[-]									**R**						
	Material	Al Alloy xxxx	[Spec]															
	Part	xxxx	[Part Number]	**R**														
	Number	xxxx	[#]	**R**														
	Temperature	495 ± 5	[°C]					**R**			**R**		**R**	**R**	**R**	**R**	**X**	**X**
	Hardness	**<X**	[BHN]										**R**	**R**	**R**	**R**	**X**	**X**
	Tensile Strength	**>Y**	[MPa]										**R**	**R**	**R**	**R**	**X**	**X**

Figure 5-5 Characteristics Matrix and information flow from Process Flow Diagram

5.4.2 Step 2 – Process Failure Mode Identification

5.4.2.1 Process FMEA

The Process FMEA was completed with substantial support from the previously used tools and exercises as shown in Figure 5-6. In addition to the Characteristic Matrix and the Process Flow Diagram applied in the first case study, this example benefitted from the inclusion of the P Diagram, which added clarity in determining noise factors or sources of variation and even more so in terms of the potential error states identified during its development.

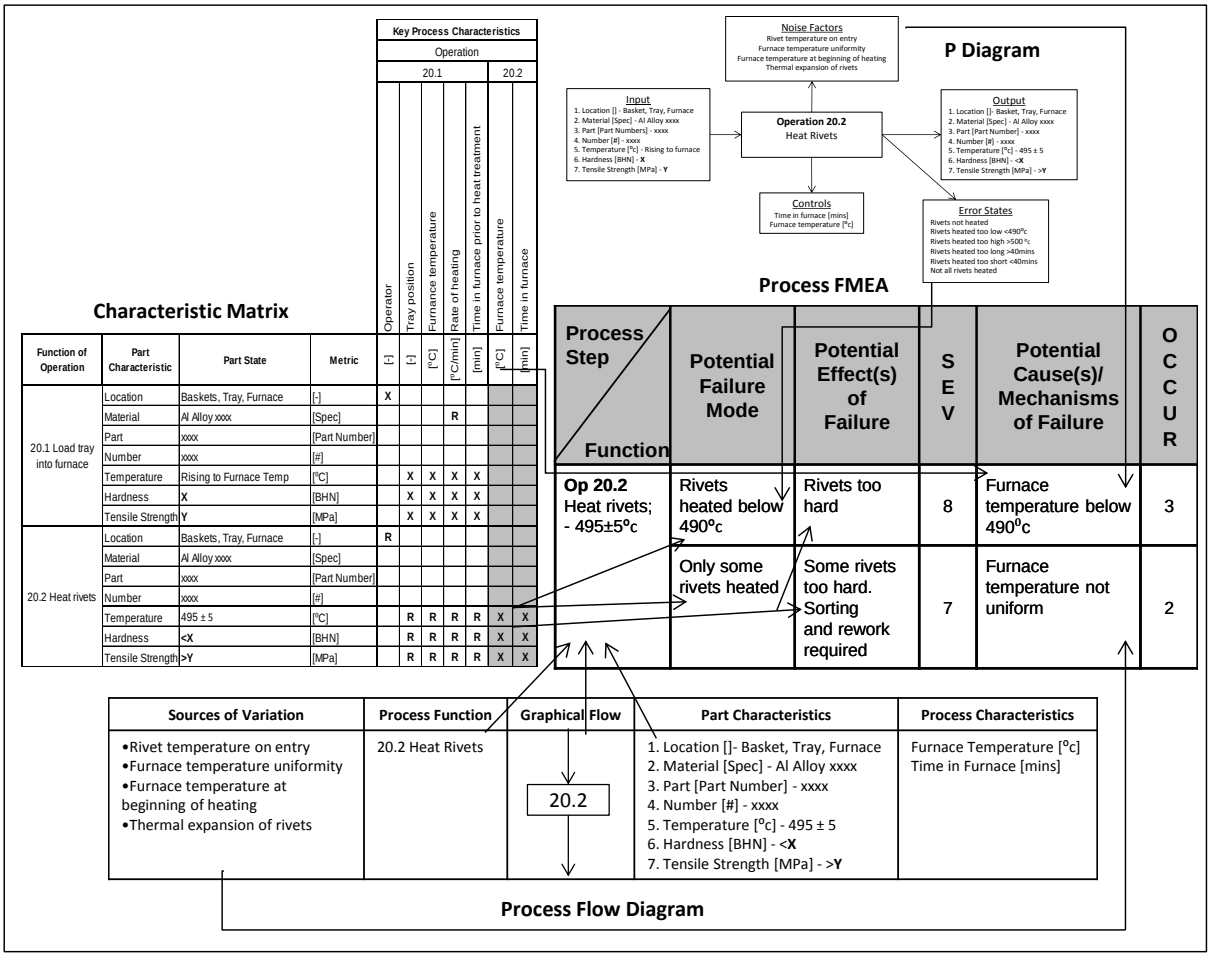


Figure 5-6 Process FMEA and supporting information flow

As a result of this additional tool, complemented by the functional decomposition through a series of levels of increasing resolution conducted at the Process Mapping stage, the scope of the Process FMEA has seen improved containment. This was demonstrated by the causes of failure being at a level consistent with the failure mode. For example, the causes in this extract

were related to the ability of the process to meet its requirements, rather than directly passing over these into the causes that may have lead the furnace to meet its requirements, which should be represented at a further level of abstraction.

The team benefitted from the structure established in Step 1 of the MFMA framework when completing the Process FMEA. Having the process and its requirements broken down in this manner allowed their time to be used more effectively, as the Process FMEA was divided into distinct process steps and their individual requirements and had the support of previous analysis prior to the start of the exercise. The Severity and likelihood of Occurrence were rated using the same criteria as the first case study, as it was deemed appropriate. The Process FMEA was completed in 15 hours, with a mix of one and two hour meetings, based on the availability of the team members.

5.4.3 Step 3 – Process Improvement

Figure 5-7 shows how the Process FMEA was used to manage process improvements in Step 3. By clearly defining the failure modes, the Process FMEA provides clear scope for the design and deployment of robust countermeasures to prevent the failure modes and their effects.

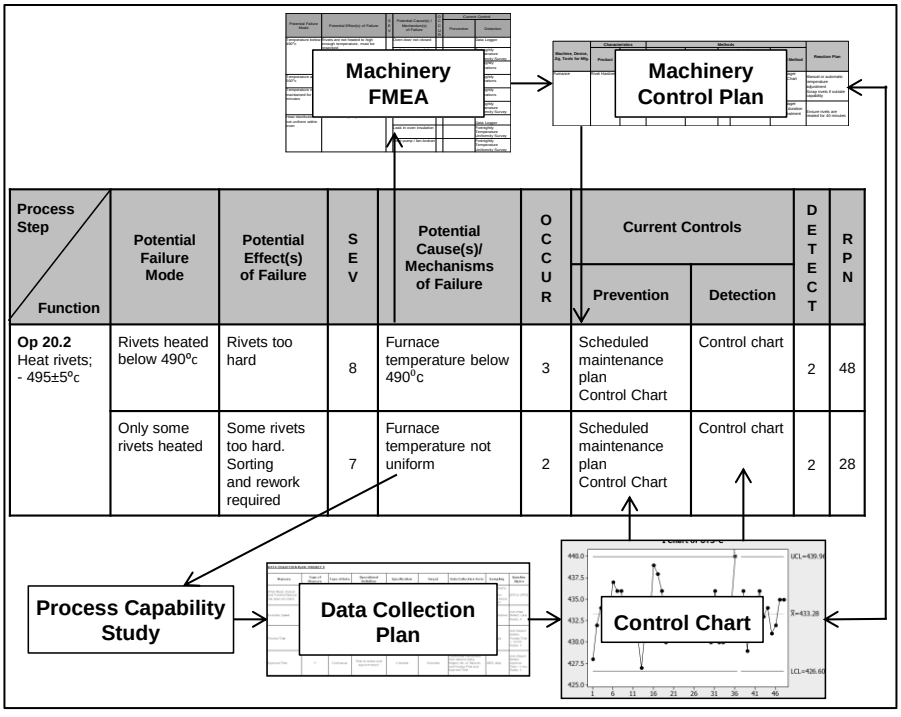


Figure 5-7 Information flow between FMEA and Process Improvements

Through the Process FMEA, the problem statement for the improvement action was succinctly defined in relation to the process requirement, and consequently contextualised. For instance, the rivets are too hard because the Furnace temperature is too low.

The Severity and Occurrence ratings of each failure mode allow prioritisation of the improvement effort. Thus, in this example, the process failure mode of the rivets being heated below the required temperature poses a greater risk to the process function than only having some of the rivets heated.

There are many tools and process used for problem solving and improvement, but these methods and techniques were not the focus of this case study. Instead the intent was to provide a framework which they can be based around to ensure efficient application and the greatest return in terms of specific process control. This step demonstrated how the output of the Process FMEA provides scope and prioritisation for these techniques, addressing the common pitfalls that are associated with them. While these tools are normally applied in conjunction with specific problems identified with a process, they can also be deployed at the process design stage, and integrated with the MFMA framework.

5.4.3.1 Machinery FMEA and Control Plan

As shown in Figure 5-7, specific failure causes provided scope for the development of preventative controls at a level which can be engineering and implemented. In this example, the failure modes are the result of the machinery potentially affecting the process' ability to meet its requirements. A cause at this level becomes a failure mode at a machinery level, which prompts a Machinery FMEA to be developed in order to understand how this failure could occur and to develop controls to prevent it migrating into the process level, causing a process failure. This translation of the failure mode into another level is characteristic of the cascade between domains in Axiomatic design, as described in the literature. In this instance, the cause of a failure mode in the 'process domain' has been transposed into a 'machinery domain'. Investigating this failure mode at this level may consequently transfer the cause of failure at a machinery level into a failure mode at a level associated with the design of the

equipment. As a result, process failure modes are understood from the bottom up, through the various levels that are required for the process' operation ensuring the countermeasures to failure are fully robust in their design.

The system for controlling the machinery is described in a Machinery Control Plan, describing the actions necessary to allow the equipment to be in a continual state of control, and the relevant outputs flow back into the Process FMEA, recorded as preventative controls used to reduce the risk of the process failure mode. In this instance, these controls come in the form of a scheduled maintenance plan which is implemented as a result of this requirement.

The ability of the control to prevent the cause of failure occurring is then rated using the Detection scale and input into the Process FMEA. Consequently, the RPN for the failure mode can be calculated and its total risk is quantified.

5.4.3.2 Process Capability Study

Figure 5-7 also shows how the Process FMEA can be used to initiate process capability studies. Through Steps 1 and 2, critical process characteristics have been identified, particularly in the Characteristics Matrix which illustrates the relationships between the process and the parts. The Process FMEA contextualises these characteristics in terms of process failures, and prioritises them. Consequently, the starting point of a process capability or Six Sigma variability reduction exercise has been achieved; to select the relevant quality characteristic and define the problem.

This provides scope to develop a Data Collection Plan, which requires the selection of an appropriate Control Chart and details the measurables the will be recorded and at what frequency. These represent steps 3 – 5 in Doty's (1996) methodology for constructing Control Charts. Subsequently, control limits can be set and assessed as data is obtained, and the process' performance can be monitored for trends that indicate when it is unstable or heading out of control. Alternatively, if the DMAIC Six Sigma methodology is applied, this would refer to the Measure phase, allowing the subsequent Analysis, Improvement and Control phases to be completed.

In this case, the temperature uniformity can be measured using thermocouples. By this means, the MFMA framework ensures that process inputs, such as temperature, are measured rather than process outputs which means control measures are used preventatively rather than reactively which is accordant with the literature best practice.

The system of data collection and use of the outputs of the Control Chart are embodied into the Machinery Control Plan, as depicted in Figure 5-7 which facilitates control of the furnace through process intervention when the control limits are breached.

In this case study, these process improvement actions were not fully established. This was due to the resource required for the scale of these actions, which would vastly out stretch what is feasible in the scope of this study. However, the opportunities were explored by the team and the mechanics investigated which would allow for continuation outside the scope of this research case study. For example, the relevant line items of the Machinery FMEA were completed.

5.4.4 Step 4 – Process Control and Validation

Once the countermeasures and controls required to prevent and to detect the failures identified on the Process FMEA are defined, a Process Control Plan was created. This is used to implement and verify the improvements, by detailing how the systems that are used to control the process are implemented for ongoing control.

Figure 5-8 demonstrates how the information developed through the course of the MFMA framework led into the Process Control Plan. The process step and function have flowed directly from the Process FMEA, using the structure developed during Step 1 of the MFMA framework that has flowed throughout the procedure. The machine, process characteristics and process specification columns have also been populated with information gathered in Step 1, which in this case was first documented in the Process Flow Diagram. The measurement technique, sample information, control method and reaction plan details have come from the process improvements developed in Step 3.

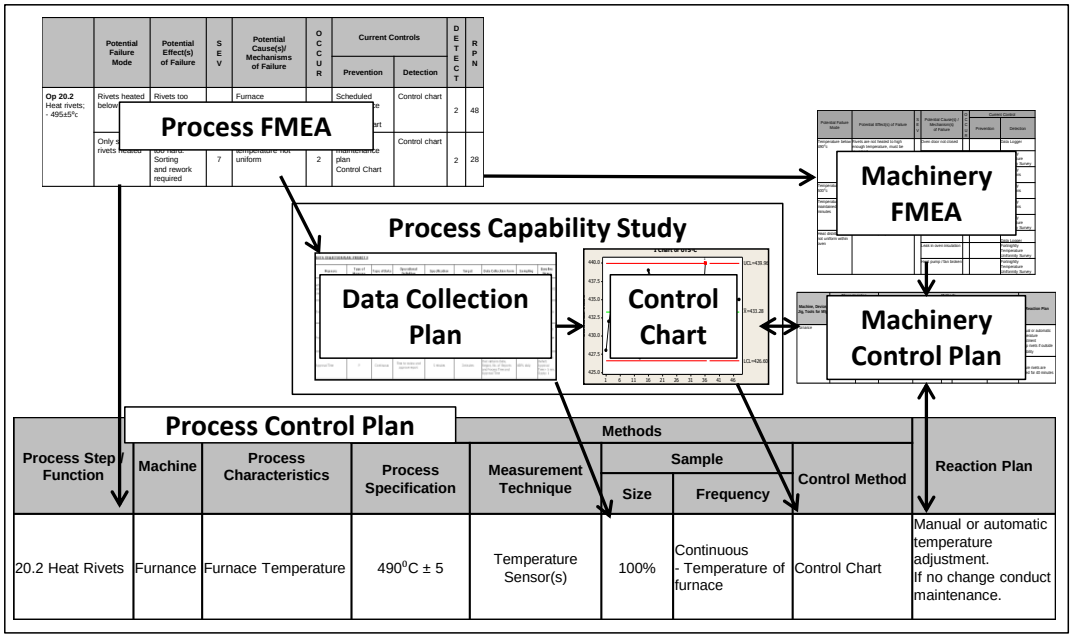


Figure 5-8 Information Flow into Process Control Plan

Consequently, the Process Control Plan is a summary of the actions required for process control that have resulted from the previous steps of the MFMA framework. Consequently, these actions are categorised by each process step and cover its functional requirements. This ensured that all of the potential failure modes identified are covered, but also that the document remained consistent, concise and manageable. Also, justification has been provided for each of the improvements that have been developed as they can be traced through the MFMA framework to provide evidence of their requirement and influence on the process.

The Process Control Plan is a living document and as the methods it describes are performed, their effectiveness can be monitored by observing the outputs from the process. If the countermeasures to failure are not fully effective, then the Process FMEA can be revisited and MFMA Steps 3 and 4 conducted iteratively.

In summary, the Process Control Plan has provided a checklist of the activities that need to be carried out in order to maintain process control, in relation to the avoidance of previously identified potential failure modes. Through the flow of information and structure provided by the MFMA framework, the pitfalls

associated with Process FMEA activities not leading to control methods and potential design changes have been addressed.

6 Discussion

6.1 Outcomes of Case Study 2

The second case study has provided validation for the proposed MFMA framework, by applying it in totality after the first two steps were initially trialled in a pilot case study and opportunities for improvement were identified. Here the outcomes of the study are discussed, with particular emphasis on the novelties of this implementation.

The enhancements made to the Boundary Diagram for the second case study have shown to be positive. By recording additional characteristics of the part, other than just the geometric features which was permissible in the previous study, the Boundary Diagram was richer and allowed the process, in terms of the changes made to the part, to be understood in greater depth. Identifying the characteristics at one end of the process, either as an input or an output, prompted their consideration not only at the alternate end but throughout the process, as achieved by Process Mapping and functional decomposition. As a result, it is clear this addition had a positive effect on mapping characteristics which allowed more interrelationships to be considered when completing the Characteristic Matrix, providing greater structure throughout the MFMA framework. Furthermore, considering the external interfaces in terms of People, Plant, Process and Part led to their identification being suitably organised and provided a context that allowed them to be covered.

In the second case study, the process was functionally decomposed through two levels of abstraction from that defined at the boundary level. This was initiated after the first case study showed that there was insufficient understanding of the process to link failure modes to their cause with consistency, as process failure modes were attributed to causes at a machinery level. Consistent with the guidelines provided by the Department of Defence (2001), deconstructing the process into different levels proved effective for understanding the function of the process. This is crucial in the complex environment of aerospace manufacture where numerous manufacturing operations are interactive with one another and a variety of interrelationships

and dependencies exist which exacerbates identification of variants and understanding of their resultant effect on the output. This is in accordance with Bartolomei et al., (2012), who discuss how an incomplete or distorted view of a system's behaviour can occur when an inappropriate level of detail is selected for analysis.

The introduction of the P Diagram has also been beneficial. Sequentially, it naturally follows on from the Process Maps, which individually defines the process' functional steps with their input and output. Consequently, in keeping with the other tools in the MFMA framework, there is a strong inward flow of information to support the tools completion, as illustrated across Figure 5-2 and Figure 5-3. At this stage, considering process failure modes, dubbed 'error states', noise factors and controls at each process step complements the subsequent completion of the Process Flow Diagram, which summarises all of this information together with the rest of the manufacturing process. To this end it also supports the Process FMEA, particularly in terms of documenting failure modes, which were not formally considered prior to the completion of this tool in the previous case study. As a result, the inclusion of this tool has resulted in improved robustness in regard to information capture and flow within the MFMA framework.

In both case studies the Characteristics Matrix, shown in Figure 4-4 and Figure 5-5, has demonstrated part to part, part to process and process to process linkages very effectively. In the second case study, identification of a variety of part characteristics at the Boundary Diagram stage led to a richer matrix, as each of these characteristics are represented for each operation, unlike in the first case study where only geometric characteristics created at that operation were recorded. However, in both cases characteristics that were required by the process specification where captured, it is just that in the previous study these were geometric and in the latter they are based on material properties. It is felt that a more consistent approach to capturing part characteristics needs to be devised, as those defined on drawings and specifications (or Conditions of Supply) may not be exhaustive enough as to allow all process failure modes to be identified through causality. That said, this is possibly a failure of the customer-supplier relationship rather than that of the MFMA framework.

As a single document, the Characteristic Matrix is very useful for providing a summarised overview of the casual relationships within the manufacturing process. This is pivotal for process understanding and for analysing causes and effects of process failures. However, it has the potential to be a very large document and has relied on appropriate scoping and scaling of the process to a manageable level so that it does not extend beyond what can be feasibly populated. Therefore, it is arguably a testament to the proceeding steps of the MFMA framework that it is able to be utilised effectively.

The completion of the Process FMEA, as illustrated in Figure 5-6, highlights the effectiveness and individual value of each of the other applied tools, but also illustrates how they are greater than the sum of their parts as the information they generate converges. Process data is provided efficiently to allow this tool to be populated concisely and consistently but also thoroughly. Functionally deconstructing the process means that the material for the first two columns of the document is pre-existing and directly transfers inwardly from the Process Flow Diagram. This alone is a huge step towards containment of what can potentially be a very large and time expensive document and improves the integrity of the information it holds when compared to the conventional approach, underpinned by brainstorming.

Continuing to consider the Process FMEA from left to right, the potential failure modes are inputted from the P Diagram. By previously isolating the distinct process requirements, and assessing potential failures in this context, failure modes are correctly attributed to the operation in which they can occur as opposed to when they might be discovered. This principle is also supported by the Characteristics Matrix, as it conveys the internal mechanics of the process by displaying how and when characteristics are altered, changed or used. Through this means, the Characteristics Matrix gives structure to identify the effects of the failure on the downstream process operations and sheds light on where, when and by what means the potential failure would be detected by the process, as it operates in its current state. For example, if a feature created at one step is required for location at a latter, or when an operator would first be exposed to a component after a failure mode could potentially have occurred. Not only does this facilitate appreciation of the pre-existing detective methods

that naturally exist within the process, but it identifies what the effects of the failure are.

Potential causes of the failure mode are supported by the Sources of Variation recorded on the Process Flow Diagram, the Noise Factors on the P Diagram and the Process Parameters on the Characteristics Matrix. These sources of information include process inputs that can and can't be readily controlled. As a result, the MFMA framework includes causes of failures associated with undesired inputs or variables beyond a state of control as well as failures that occur as a consequence of a failure within an incidental system, be it tooling, machinery or a process within the manufacturing process that consequently needs to be analysed at an increased level of detail.

The second case study illustrated how the Process FMEA provides a direct input into process improvements that will improve the reliability and robustness of the process. Identifying a potential failure mode specifically related to the requirement of the process allows improvement activity to be relevant to the control of the process, rather than having tools such as process capability studies or Six Sigma projects applied without context. Antony (2004) and Nonthaleerak and Hendry (2008) highlight the issues associated with this behaviour, describing how the identification and definition of process improvements is challenging and costly. Consequently, the Process FMEA details precisely what the process needs to achieve, how it could fail to achieve this and what the effects could be, whilst also providing a priority scale of which are the most critical failures through the Risk Priority Number. Therefore, the inheritance of the improvement action has been provided with a strong and clearly scoped problem statement, addressing problems detailed both in the literature and in the Company's current practice.

It must be made clear that Process Capability or Six Sigma Studies are not the only improvement activities that can occur as a result of using the MFMA framework. The extracts in the second case study show a failure mode associated with capability of the furnace to maintain a uniform temperature within the process specification. In this instance, a Process Capability Study provides an effective method of monitoring the furnace's performance and

prevents processing rivets when the process is not able to heat them as required. However, the countermeasures in this area can be anything from the redesign of tooling, to introduction of a Poka-Yoke or error proofing device, additional training of staff or, if the risk is perceived as insignificant, doing nothing at all.

In the final step, the outputs of the improvement activities are inputted back into the MFMA framework. This addresses the recorded issue of FMEA studies not leading to Process Control Plans and improvement. The information flow within the MFMA framework has led to control methods being identified in relation to failure modes that they are trying to prevent in a clear and consistent way. This also ensures that the Process Control Plan contains detailed instruction related to each of the process failure modes identified. The process step and function are recorded with the means by which this is achieved, how these are controlled and the escalation required if the process strays out of control.

6.2 Review of MFMA Framework

Figure 6-1 provides an overview of the MFMA framework that has been developed as a result of the two case study implementations, and illustrates the four high level steps, their objectives, the tools that are used to achieve them and the information flows between them which are the characteristic features of the framework.

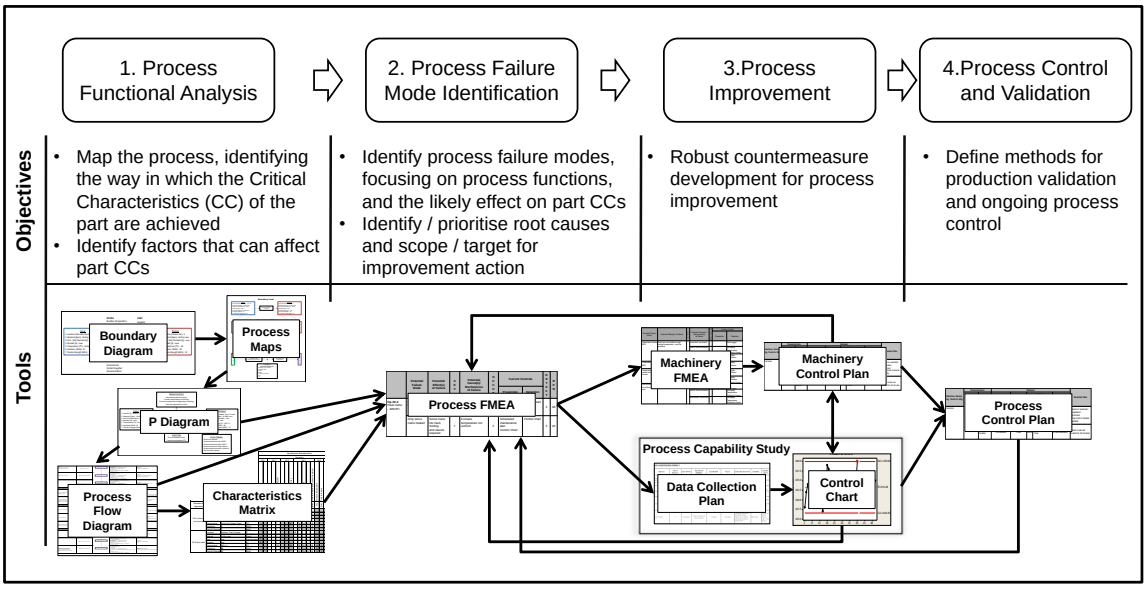


Figure 6-1 Overview of the MFMA Framework with flows of information illustrated

This framework has been developed based on the four higher level steps of the FMA framework, as presented by Campean and Henshall (2009). Through the case studies, detailed guidelines have been established for the implementation of this framework. Existing process tools have been developed, particularly the Characteristics Matrix, and sequenced in order to enable a flow of information that supports their completion and contextualises them within the framework as a whole.

In order to review the effectiveness and suitability of this framework, it is necessary to return to each of the research questions provided in Section 3.4.2. These are referred to under the following headings.

6.2.1 Managing Complexity

Through the completion of two case study applications, on real life manufacturing processes, it has been demonstrated that the MFMA framework is effective at supporting the analysis of complex manufacturing procedures by providing a structure to guide the investigation which leads into the development of specific process control methods. This has been shown by completion of each of the tools, which are demonstrated in the extracts displayed in Chapters 4 and 5.

Together, the case studies have shown that using the Boundary Diagram to define the manufacturing process at the first step has allowed the analysis to be contained, which is demonstrated through the completion of the subsequent tools and methods. Setting these limits early on prevents scope creep during the detailed analysis, which can be disruptive and time consuming.

Once the boundary has been set, analysis of the process within these limits has been facilitated using the Process Maps. Through iterative functional decomposition, akin to the methods used for system analysis covered in the literature review (Department of Defence (2001), Mendling et al. (2008), (Campean et al., 2011)), the process is deconstructed through a series of levels of abstraction from the original, high level function described in the Boundary Diagram. These levels allow the team to focus on the process in distinct

operations, which is manageable but consistent within the context of the overriding requirement of the manufacturing system. A constant numbering format along with simple protocols for defining and describing operations has enabled this approach.

6.2.2 Information Flow

Inspired by FMA, the MFMA framework has been designed to facilitate a flow of information between the tools so that they can be completed efficiently and concisely, whilst minimising unstructured brainstorming.

As shown in Figure 6-1, there is a clear information flow from the beginning to the end of the MFMA framework that connects every tool. The part characteristics that define the state of the input and the output of the process are identified and recorded at the initiation of the framework and can be traced throughout the entire procedure.

As noted in both the case studies, including the second which featured the additional P Diagram, other than the Boundary Diagram, none of the tools start as a blank, as information from a preceding tool can populate multiple elements of the subsequent tool. When completing each of the tools it is straightforward to understand what information is intended to be added and it builds sequentially on that provided from its predecessor. The flow of information provides a narrative and contextualises each of the tools and their objectives and as a result, their output is greater than the sum of their parts. As each tool leads to another, they are more purposeful and there is a direct linkage between the work required to complete them and the actions that result. Consequently, the flow of information addresses issues found with exercises being completed without support and to no avail. This is particularly true of FMEAs as standalone documents which are commonly difficult to comprehend, time consuming to complete and from which no benefit is expected.

6.2.3 Functional Understanding

The MFMA framework develops an accurate understanding of the required functions within a manufacturing process. This is achieved as a result of the functional decomposition, previously described in this discussion for its effectivity at managing the complexity of the process.

The process functions are determined during the decomposition by assessing the requirements of the process that are described in terms of the part states before and after each step. This clearly defines the transformation that must be achieved by the process. As the process is documented at levels of increasing resolution, the functional mechanics by which it achieves its objective become more refined. Consequently, the specifications of various aspects of the process including the operators and machinery become known. This technique is essential when identifying the root cause of failure modes and analysing the relationships between process characteristics and part characteristics that achieve the process function.

6.2.4 Identification and Prevention of Failure Modes

As the MFMA framework leads into the Process FMEA in a step by step, pragmatic fashion, this regulates information generation and discussion at an appropriate rate and creates a shared understanding before the Process FMEA is begun. When contrasted with the historic method of approaching FMEA studies, and the associated pitfalls described in Section 2.6.6, the MFMA framework allows the FMEA to be completed much more efficiently and concisely.

MFMA offers opportunities for brainstorming and ‘off the wall’ thinking within set boundaries, which lessens the effects found using Advanced FMEA and its binary approach that was found to limit teams thinking to items closely related to the process model.

By having a defined step after the failure analysis half of the FMEA, MFMA ensures that the prevention of failure modes is addressed and that there is an output of the study.

6.2.5 Feasibility of Deployment within the Company

Functionally, the MFMA framework has demonstrated that it can feasibly be deployed within the Company. The information required to complete each of the tools in Step 1 should be obtainable and pre-existing in some form within the Business, either in part drawings, process specifications, ‘Conditions of Supply’, machinery guidelines, maintenance plans, industry standards and so forth, or in the knowledge of the employees.

Furthermore, although some form of investment will be required for the training necessary to familiarise users with the principles, toolsets and mechanisms of the MFMA framework, there is no expensive hardware or software needed in order to begin using the methodology. The Company currently provide training on some tools that are present within the MFMA framework. For example, Process Mapping is conducted as part of cross functional teams. Whilst these tools may presently be used in a slightly different format and structure to that in MFMA, it suggests that their introduction will not come as a radical addition. Also, employees will be familiar with the concept of improvement projects, with Six Sigma studies beginning conducted within the Company to some degree, and therefore should be aware of the need for their input into team meetings. Further to these points, the impacts of completing the MFMA framework with a team within the Company are discussed in detail in Section 6.3.

Therefore, there should be no hard or bodily resistance to the introduction of the MFMA framework. The most significant barrier, as is often the case with the introduction of new strategies, will be cultural, associated with communicating the need for such a framework, convincing others that the benefits can be realised and securing the required buy in to allow the implementations to prove successful.

6.2.6 MFMA Limitations

Unquestionably, one of biggest disadvantages of the MFMA framework is that it comes at a significant time expense. Getting teams together, discussing the various aspects of the process, collating information and maintaining all of the documentation means that projects are likely to span over months, even for a relatively short process.

Another difficultly associated with the MFMA framework is the management of all the documentation. Some of the documents have a tendency to become very large, which can make them hard to view particularly when during a team meeting. This is typically true of the FMEA, although this can be still be conveniently printed and viewed in a relevant section, but the Characteristics Matrix is more of a challenge to demonstrate in totality as this expands in both the horizontal and vertical axes. Furthermore, as the MFMA framework is used

it is likely to go through iterations and reviews of the information that populates the tools. Maintaining consistency between each of the tools, so that they are all representing the most up to date data and analysis, can require a lot of time. These difficulties provide clear opportunity for the development of software that can link the tools together so that changes to on one tool are automatically made on the relevant documents. This would also enable tools to be automatically populated. The second case study demonstrates how part characteristics and process operations are consistent enough to facilitate the development of such a solution.

Despite the structure that is provided by the MFMA framework, the success of the analysis is only as good as the individuals that conduct it; true of both the team members and the facilitator. It is dependent on reliable data being provided in order to give the best results. However, this weakness is commonplace for any method or system of analysis, as at some point there will be some level of reliance on human input in order to be effective. Therefore, this is not a limitation that is unique to MFMA.

6.3 Team Influence

Completing the second case study with the help of a team has proved to be an effective exercise and has shown that the MFMA framework could feasibly be performed by personnel within the Company. Throughout the second case study, it was demonstrated that the tools are of a manageable size to be populated by a team together, and the information they require can realistically be obtained from staff members within a meeting, whilst occasionally requiring consultation of process documentation and standards.

The tools provide structure for team meetings, as each of them have a clear objective and the way that they build on information and analysis generated through the previous step allows the requirement from the team to be contextualised. As a result, other than the initial Boundary Diagram which starts the MFMA framework, none of the tools begin as a blank and consequently this minimises the level of brainstorming, which leads to inefficiency in process analysis. Furthermore, as the MFMA framework has broken down the acquisition of information for the central Process FMEA through the use of the

individual tools, the team meetings have an achievable objective and a clear focus that is tangible to the team members. This is clearly advantageous over working towards the completion of what is effectively an endless Process FMEA. Also, the progress of the team against each of the tools can be easily understood, as the scope of the analysis is maintained, but refined and divided throughout the MFMA framework. This is particularly true of the Characteristic Matrix and the FMEA. The Characteristic Matrix can be drawn up as soon as the Process Flow Diagram is completed and should not require significant addition or removal of line items throughout its completion. This means that extent of the document and the progress against its completion is immediately obvious. As for the FMEA, the functional decomposition of the process into operations provides a measure for progress as each is completed. These are minor aspects of the framework but, in terms of completing work as a team and managing the work as a project, with progress reports potentially required to senior management, these are useful additions.

Completing the tools together prompts the discussion of the process' operation. This promotes critical and abstract thinking between the team as it provides an opportunity for the different members to communicate their views and challenge the views of others as information is gathered to populate the tools. This does prove costly in terms of time and it is evident that conducting the first case study as an individual allowed things to progress quicker and more readily. However, it is arguable that this debate and exchange of knowledge is where the real value in team work lies, as a shared appreciation and understanding of the process from other stakeholder's perspectives is undoubtedly beneficial to the successful operation of the process. Furthermore, it is crucial that this common understanding, as well as the language that comes with it, is developed leading up to the FMEA, if it is to be completed most effectively. It would be interesting to observe a scenario where a single team member joined in at the FMEA stage, without participating in the functional analysis completed by the rest of the team.

Delays and complications are also experienced when having to schedule and reschedule meetings in response to the team members' availability, which can lead to inconsistent gaps between sessions. This experience is not likely to be

so detrimental in future practice for several reasons. Firstly, MFMA will have the greatest impact when applied during the planning of a new process, at which point the team involved would be entirely focussed on this task, rather than in this case study where this was additional and separate to their day to day work. Also, regardless of the timing of the application, it is believed that the meetings would have been able to have a greater priority to the team if this was not a developmental activity. It is advisable that if the framework is adopted fully, that the facilitator is of significant seniority to facilitate a timetable of sessions.

Furthermore, as the team collaborates to complete each of the tools they create their own rules and definitions to use throughout the MFMA framework. This was observed during the Process Mapping exercises in the second case study, as it was agreed by the team as a whole that, as a standard, they would separate different process operations by transportation activities at the first level of abstraction from the Boundary Diagram.

6.4 Comparisons with FMA

As intended, the MFMA framework has adopted the four higher level steps and underlying philosophy of FMA. These principles have worked well, which is unsurprising. Understanding the system before identifying potential failures and subsequently designing and implementing countermeasures is a logical methodology, regardless of whether it is in relation to a product or a process.

Furthermore, MFMA has inherited the functional approach to systems analysis, as used in FMA. Where FMA uses the System State Flow Diagram, MFMA uses functional Process Mapping to deconstruct the process into a hierarchy until an appropriate level for analysis is achieved. In FMA, the ‘appropriate level’ is achieved when the function can be achieved by hardware. In MFMA, the level is less precise. In some instances, when machinery is used to meet requirements the same definition can be applied, but often transformations in manufacturing have more human interactions than in system design. MFMA has also used a flow of information between the tools that is a defining feature of FMA.

Within the first step, MFMA requires a more rigid and sequential approach to FMA, which can be begun with either the Boundary Diagram, System State

Flow Diagram, Interface Matrix or Function Tree as stated by Campean and Henshall (2009). In MFMA, it is clearly essential that the Boundary Diagram is used first to define the beginning and the end of the process before it is deconstructed, and the part and process characteristics and their relationship are analysed. Fundamentally, the process would not work if the tools were not ordered in this way. Of course, each of the tools can be used iteratively at this stage, being revisited and updated as more knowledge is gained, but they still need to be approached in this order.

6.5 Suitability of Case Studies

The case studies have provided an effective environment for the MFMA framework to be trialled upon. Both the processes that have been used are real manufacturing processes that the Company operates, and therefore provide 'real life' validation in terms of the information that the framework would be expected to hold.

However, the framework has only been applied to existing processes at this stage. Although, this was appropriate for this research, in order to properly test the effectiveness of the MFMA framework in the environment where it can have the largest potential impact, it needs to be trailed during the development of a manufacturing process. Furthermore, the case studies have not demonstrated fully the improvements have been made and the effects that these have had on process performance, but this was never the intent. Rather than illustrate the effectiveness of the improvements that can be made to a process, the motive was to develop a process that can be used towards making processes robust to failure and to that aim the case studies have been suitable.

The case studies selected for this research have both been used for component manufacture. The MFMA framework requires testing in sub assembly and final assembly scenarios in order to assess its ability as a generic method that can be universally applied. These manufacturing environments will further assess the frameworks ability to manage complexity as multiple parts and fixtures come together and interact with one another, with potential failure modes different to those at detail manufacture. This may lead to the identification of additional

casual relationships between the parts and the process, which might require redesign of some MFMA tools such as the Characteristics Matrix.

Furthermore, as the two case studies did not apply an identical MFMA framework, as the second was use to incorporate improvements to the weaknesses identified in the first, the ability of them to act in a truly replicative form and to add robustness to the results is slightly compromised. However, as the majority of the applied framework was identical and an additional case study allowed extra facets to be incorporated and improvements trialled, it is perceived as justifiable.

6.6 Advancements on Literature

This research has made several advancements to the literature surveyed in Section 2. Most significantly, it has demonstrated that the FMA framework, as presented by Campean and Henshall (2009), can be taken and adapted for use in a manufacturing process context. This provides evidence to suggest that the underlining principles and strategy of FMA are fundamental and consequently can potentially be applied to improving robustness in a variety of systems.

In more specific terms, the MFMA framework has made indirect progression on the Advanced FMEA procedure developed by Kmenta et al., (1999). Despite operating slightly differently, the MFMA framework uses a similarly function based approach to that used in Advanced FMEA, but it is one that is less restrictive. However, the MFMA framework provides the opportunity to ‘close the loop’ with Step 3 and 4 used to design, develop and implement the countermeasures to failure; something that is vacant in Advanced FMEA.

Furthermore, the Characteristics Matrix developed and deployed in this research demonstrates notable expansion on those provided by Carrión et al. (2007) and Ford Design Institute (2004). In the case study extracts provided it is not only clear that there is greater opportunity to add information, such as metrics for both part and process characteristics, but also that the data is greater refined. The result is that linkages and interrelationships within the process are more visible and can be identified and analysed at a more detailed resolution.

Finally, the full and consistent mapping of process and part characteristics throughout the MFMA framework facilitated by the information flow between each of the tools and particularly clear in the second case study, shows novelty over procedures such as APQP and Six Sigma.

6.7 MFMA Dissemination

6.7.1 MFMA Process Documentation

The MFMA process has been documented in a comprehensive handbook for use within the Company. Due to the size of this document, and because it is now owned and governed by the Company, it is inappropriate to demonstrate here in full within this thesis. However, an extract can be found in Appendix E.

The MFMA framework handbook has been developed with the intention that it can be practically used by employees throughout the business hierarchy. There are high level overviews of the issues that the MFMA framework addresses and how this is achieved, useful for higher management, but enough detail to act as a full, step by step guide that staff can use to work through the process.

In terms of content, the handbook includes the following;

- Introduction and background
- A high level overview of the MFMA process
- A detailed step by step guide of the MFMA framework, including project management activities for the different stages and descriptions of the required team roles
- Annotated worked examples of each of the tools, with a full description of the different elements and tips for their management and completion
- Full case study applications of the framework on existing processes within the Company
- Blank templates of each of the tools
- Glossary of terms
- A bibliography and further reading list

The handbook was delivered to the Company at the closure of the KTP project and is owned by the Manufacturing Capability department.

6.7.2 Adoption by the Company

Overall, the development of the MFMA framework has been a success for the Company, providing a system that can be readily adopted. This is supported by the following statement, quoted from the KTP Final Report which was submitted by both the University of Bradford and the Aerospace Company at the completion of the project;

> *"The KTP has delivered a framework which can be used to fully understand the failure modes in our complex production processes. The framework has been developed in a way that it fits into the culture and workings of our Company, thus allowing it to be accepted and used by the team members. The delivered handbook provides all the training needed to use the framework."* – Industry Supervisor, KTP Final Report (2013).

The MFMA framework builds on the transformation efforts that the Company are pursuing which have been described in Section 3.1. Fundamentally, it offers a strategy to shift towards preventative rather than reactive action, a transition from quality control to assurance, which is the step change required to facilitate a cost effective ramp up in production.

At an operational level, MFMA is structured, systematic and sequential so that it provides rationale and maintains scope for each of the toolsets, ensuring that the efforts of the team are contextualised and the outputs of activities are acted upon. This addresses the weaknesses identified with the Company's current practice of Lean and Six Sigma techniques.

Six Sigma projects can be integrated into Step 3 of the MFMA framework, 'Process Improvement'. The 'DMAIC' process that is used by the Company can be easily applied at this stage, not only benefitting from the problem definition provided by the analysis in Steps 1 and 2, but also from the avenue to directly incorporate the outcomes of the study back into the production environment through the Process Control Plan in Step 4.

There is significant potential for deployment of the MFMA framework within the Company. Due to the generic nature of the methodology and its components, it

seems realistic to suggest that it could be applied to business operation processes as well as manufacturing processes, with only minor tailoring. Furthermore, the framework can be adapted to host a variety of individual tools if preferential to the team or the context of the application. For instance, a Fishbone or Ishikawa Diagram could feasibly be added to aid in root cause analysis, permitting it is suitably placed so the overall methodology isn’t derailed.

7 Conclusions

Aerospace manufacturers are under pressure to reduce production costs, whilst simultaneously increasing production rates in order to remain competitive in the global defence market. This market is associated with high value, low volume manufacturing, in which high scrap and concession rates lead to spiralling costs that eat into profits. Consequently, there is a requirement to produce expensive components and assemblies right the first time through.

MFMA is a systematic methodology, based on FMA after its success in automotive system design, which has been developed to facilitate the identification of potential failure modes to allow their prevention through the implementation of countermeasures. The bottom line aim is to reduce cost by developing robust manufacturing processes that reduce waste and the associated costs.

The MFMA framework has been developed to identify the functional requirements of the process in order to understand how it could fail to function. Consequently, corrective action can be taken in order to prevent the root cause of the failure from occurring leading to improved robustness and subsequent reductions in the cost of poor quality.

FMEA is a tool that has been used historically to ensure reliability in product and process designs. However, it also has many weaknesses that have detracted from its success in industry. The MFMA framework uses the FMEA as a central tool and addresses the associated issues with this technique by supporting it with a number of additional engineering tools in a synergistic manner. The novelties of this approach in this context are;

- The structured top-down approach to process decomposition achieved through functional mapping
- The use of the P Diagram and the Process Flow Diagram to identify and document process noise factors, and the use of the Characteristics Matrix to identify part and process characteristic linkages
- A consistent and coherent flow of information between the tools, that facilitates the development of a concise Process FMEA and robust

Process Control Plans, addressing the pitfalls of conventional FMEA deployment

7.1 Main Conclusions

This framework has been validated through two case study implementations and the following conclusions have been made;

- The FMA philosophy and high level steps can be effectively applied to the analysis of manufacturing systems
- The MFMA framework can be used to identify part and process linkages using the Process Maps, P Diagram, Process Flow Diagram and the Characteristic Matrix
- The functional mapping is effective, but decomposition is required in order to allow the failure analysis to be conducted at an appropriate level so that root causes are identified correctly
- The order of the tools is appropriate and the flow of information between them is strong and conductive to the analysis
- The MFMA framework provides sufficient structure to the allow FMEAs to be completed efficiently and effectively without being overly restrictive
- The MFMA framework can be completed by team members within the Company and the scale of the tools is appropriate
- A Characteristic Matrix is an effective tool for the analysis of relationships between process and part characteristics. This tool is a very useful resource for identifying the cause and effect of process failure modes as it allows downstream and upstream influences to be identified.
- The tools, particularly the Characteristics Matrix, have the potential to become large which can make them difficult to work on as a team and to update with changes

7.2 Opportunities for Further Research

The following recommendations are made for future research;

- An implementation of the MFMA framework should be conducted on an assembly process to identify the suitability of the method in this environment
- The MFMA framework needs to be trailed during the development of a new manufacturing process to allow a full validation of the process. In order for the effectiveness of the MFMA framework to be thoroughly assessed, the costs associated with the setup and operation of the new process should be compared with those of an existing and comparable (in terms of scale, manufacturing rate, component cost and so forth) process. This would require the selection and comparison of key performance indicators between the new and existing process, which could include mean time between failures (MTBF), scrap rates and process capability indices.
- Investigations into the best configuration of MFMA teams. This could include the optimum number of team members and which of the company roles should be represented.
- Develop software to support the MFMA framework. This would include digital templates of each of the tools and it is recommended that the documents are linked together so that changes that are made are consistent across all of them.
- Investigate the outcomes and opportunities of using FMA and MFMA in parallel, developing new products and the process for manufacture concurrently.
- Develop the MFMA/FMA frameworks and apply to other systems outside of design and manufacturing. For example, business processes or I.T. systems.

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Appendix

A. Severity Rating Scale

B. Occurrence Rating Scale

C. Detection Rating Scale

D. Original KTP Plan

E. MFMA Handbook Extracts

A. Severity Rating Scale

Effect	Criteria: Severity of Effect	Ranking
Hazardous-without warning	May endanger machine or assembly operator. Very high severity ranking when a potential failure mode affects safe product operation and/or involves noncompliance with government regulation. Failure will occur without warning.	10
Hazardous-with warning	May endanger machine or assembly operator. Very high severity ranking when a potential failure mode affects safe product operation and/or involves noncompliance with government regulation. Failure will occur with warning.	9
Very High	Major disruption to production line. 100% of product may have to be scrapped. Product/item inoperable, loss of primary function. Customer very dissatisfied.	8
High	Minor disruption to production line. Product may have to be sorted and a portion (less than 100%) scrapped. Product/item operable, but at a reduced level of performance. Customer dissatisfied.	7
Moderate	Minor disruption to production line. A portion (less than 100%) of the product may have to be scrapped (no sorting). Product/item operable but at reduced level of performance. Customer dissatisfied.	6
Low	Minor disruption to production line. 100% of product may have to be reworked. Product/item operable but at reduced level of performance. Customer dissatisfied.	5
Very Low	Minor disruption to production line. The product may have to be sorted and a potion (less than 100%) reworked. Defect noticed by most customers.	4
Minor	Minor disruption to production line. A portion (less than 100%) of the product may have to be reworked on-line but out-of-station. Defect noticed by average customers.	3
Very Minor	Minor disruption to production line. A portion (less than 100%) of the product may have to be reworked on-line but in-station. Defect noticed by discriminating customers.	2
None	No effect	1

B. Occurrence Rating Scale

Probability of Failure	Possible Failure Rates	Ranking
Very High: Failure is almost inevitable	≥ 1 in 2	10
	1 in 3	9
High: Generally associated with processes similar to previous processes that have often failed	1 in 8	8
	1 in 20	7
Moderate: Generally associated with processes similar to previous processes which have experienced occasional failures, not in major proportions	1in 80	6
	1 in 400	5
	1 in 2000	4
Low: Isolated failures associated with similar processes	1 in 15,000	3
Very Low: Only isolated failures associated with almost identical processes	1 in 150,000	2
Remote: Failure is unlikely. No failures ever associated with almost identical processes	≤ 1 in 1,500,000	1

C. Detection Rating Scale

Detection	Criteria: Likelihood the Existence of a Defect will be Detected by Process Controls Before Nest or Subsequent Process, or Before Part or Component Leaves the Manufacturing or Assembly Location	Ranking
Almost Impossible	No known controls(s) available to detect failure mode	10
Very Remote	Very remote likelihood current control(s) will detect failure mode	9
Remote	Remote likelihood current control(s) will detect failure mode	8
Very Low	Very low likelihood current control(s) will detect failure mode	7
Low	Low likelihood current control(s) will detect failure mode	6
Moderate	Moderate likelihood current control(s) will detect failure mode	5
Moderately High	Moderately high likelihood current control(s) will detect failure mode	4
High	High likelihood current control(s) will detect failure mode	3
Very High	Very high likelihood current control(s) will detect failure mode	2
Almost Certain	Current controls(s) almost certain to detect the failure mode. Reliable detection controls are known with similar processes.	1

D. Original KTP Plan

Below is the plan originally submitted for KTP Project KTP008646. There were some minor changes, including the area of the second implementation, which were all previously agreed during Local Committee Meetings.

Task No.	Task description	Effort (months)	Outputs & key decision points
1	**Knowledge Base & Company induction**	**0.5**	
			Induction completed
2	**Training and development including KTP modules 1, 2, 3 and 4 and mini project (altogether calculated as 10% of total project time).**	**2.4**	Personal Development Plan (PDP) planned and implemented
			Modules and mini-project complete
3	**Associate to complete detailed action plan, *e.g.* including a Gantt or Critical Path Network, and risk assessment, for the entire project and a detailed task list for all project stages.**	**0.5**	
			Detailed action plan
4	**Associate holidays**	**3**	20 days entitlement plus 9 statutory, total 58 working days = 11 weeks 3 days, i.e. approx 3 months.
Stage total		**(5.9)**	
Project Stage 1 – Benchmarking Manufacturing MFMA Best Practice			
	Activities which have commonality with activities in the other 2 KTP projects are marked with an asterisk.		
Task 1.1	***Establish Project Organisation:*** Define team members and Company stakeholders (steering) group, roles and responsibilities.		Project organisation chart
Task 1.2	***Conduct Literature Review on FMA Tools and Practices:*** Carry out a critical review of literature on Failure Mode Avoidance tools and practices. The review should focus on, but not be limited to, tools that support a predictive process driven manufacturing engineering and production approach. This would include, for example, Process FMEA and Advanced Product / Process Control Planning. Prepare a critical report on the literature review, highlighting the advantages and		

	potential shortcomings of the conventional process analysis tools (PFMEA in particular). Review FMA support tools and their use in a broader FMEA context, and discuss possible ways in which these tools could enhance the PFMEA process (discussion included in the report).	**0.6**	Literature review completed; Report on literature;
Task 1.3	***Carry out Industry Best Practice Survey:*** Based on literature review and with support from the Company and the University, select a number of relevant (on the basis of product / manufacturing complexity, volume / rate) manufacturing companies to visit to identify/review industry best practice for the use of Process FMEA and other MFMA supporting tools, including the broader supporting context in which the FMEA is developed and used. Identify the key attributes of best practice and prepare a report. Prepare an Industry Best Practice Survey report. Report to Company by report and seminar.	**1**	Benchmarking report. Company report and seminar
Task 1.4	**** Critical Review of Company's manufacturing processes and practices:*** Study / develop an understanding of the manufacturing processes which provide scope for the study. Review current manufacturing engineering practices within the Company, focusing in particular on process steps aimed at minimising the occurrence of manufacturing failures during the launch and on-going use of manufacturing processes. Review to be conducted both at a macro level from a company-wide perspective and at detailed level in terms of specific manufacturing processes similar to any subsequent pilot implementation of MFMA and Process FMEA (see Project Stage 3 & 4). Evaluate current state of MFMA KPIs (throughput, scrap and rework rates, first time through rate, machine utilisation, process capability, Cost of Quality) for representative manufacturing processes (CNC machining and carbon composite manufacturing) Prepare a report on the findings.	**0.5**	Technical report on current manufacturing engineering practices within the Company, and a critical evaluation of different approaches. Current status of KPI tracking established; On-going KPI tracking set up.
Task 1.5	***Develop and Formulate Best Practice:*** Combine findings from the literature review, Industry Best Practice survey and review of the Company's manufacturing processes towards the development of a Manufacturing FMA (MFMA) best practice process. It is anticipated that the MFMA process will have PFMEA at its core, directing and documenting Failure Mode Avoidance investigation and actions. In-depth analysis of FMA support tools will be required in order to develop a coherent process that enhances the PFMEA process in identifying potential manufacturing failures, establishing effective countermeasures and validation of these countermeasures during the lead up to and during on-going volume production. Since the MFMA process aims to map *all* potential failure modes, the scope of the MFMA will cover		Recommendation for MFMA

	capability of processes and machinery. Develop a prototype case study to illustrate the proposed MFMA process and review this (in the context of the whole FMA process) with the Company. Incorporate modifications based on feedback received as required. ***(Stage total)***	 **1** **(3.1)**	best practice process.
Project Stage 2 – Develop the MFMA Process and Plan for its Implementation			
Task 2.1	***Conduct a Gap Analysis and Develop an Action Plan for Implementing Manufacturing FMA*** Identify areas of strength and weakness within the Company in relation to the proposed MFMA process. Establish strategic targets for key MFMA KPIs, Develop an action plan including training to build on strengths and overcome weaknesses. Identify potential pilot areas for initial implementation of MFMA process bearing in mind the other KTP projects to which this project is directly related. Review analysis with the Company and agree area for pilot of MFMA process.		GAP analysis ***Decision point 1***: Pilot area and scope for MFMA implementation
Task 2.2	***Develop MFMA process implementation detail*** Research and develop detailed MFMA process steps based on iterative application of MFMA tools. Develop pro-formas and other documents to support structured team work, documentation and data gathering, and information flow throughout the process. PFMEA should be central to this process with the PFMEA document ultimately storing the results from the analysis – in terms of functions, failure modes and effects, causes, countermeasures and results of countermeasure validation,.	**0.5**	Detailed MFMA Process outline, including: • Process Tools; • Integration & information flow; • Documentation requirements.
Task 2.3	***Develop MFMA software support package*** Evaluate existing software packages that might support the implementation of the MFMA process, including forms and software packages already existing in the Company (e.g. for FMEA). Select a suitable package if one exists or if not develop appropriate software support based on expertise of KTP Associate (for example, using Microsoft Excel).	**0.5**	***Decision point 2***: Software support package selected.
Task 2.4	***Plan and Schedule MFMA Pilot*** Using appropriate MFMA tools such as process mapping establish the scope for the MFMA pilot area identifying the boundary for the analysis. Identify the manufacturing processes or key parts of manufacturing processes to be subjected to in-depth analysis by the MFMA process. Develop an action plan for the in-depth MFMA analysis. Agree the action plan for in-depth analysis with the Company. Develop a Deployment plan and schedule for the roll-out of training and pilot implementation of the MFMA process.	**0.5**	

	Plan to be signed off by the Company.		Pilot deployment plan and schedule
Task 2.5	***Develop training package for MFMA Pilot deployment*** Develop a training package to support the pilot of the MFMA process based on analysis conducted during tasks 2.1 to 2.3	**0.25**	MFMA Training package
	(Stage total)	**0.25** **(2.0)**	
Project Stage 3 – MFMA Pilot Implementation Phase 1: Titanium Parts Manufacturing Processes / CNC Machining Processes			
Task 3.1	***Form Team + Roll out training*** Form team for MFMA pilot area and agree roles and responsibilities. Conduct training as an integral part of team workshop/ application meetings in which Tasks 3.2 to 3.5 are completed	**0.25**	Training Matrix
Task 3.2	***Identify Key Product and Manufacturing Process Characteristics*** Carryout a high level analysis using appropriate MFMA tools to identify key product and process characteristics. Identification of key product characteristics will be based on information supplied by the product designers and the use of appropriate FMA tools such the loss function. Key manufacturing characteristics to be based on the high-level cascade of characteristics through the pilot area manufacturing processes. The identification of key manufacturing characteristics will be facilitated by the use of appropriate MFMA tools e.g. process mapping/flowcharting and characteristic matrix.	**1.0**	Process Map Key product and manufacturing process characteristic matrix
Task 3.3	***MFMA Analysis of 5 axis CNC Machining Processes*** Apply the MFMA process to the 5 axis machining stages. Identify potential manufacturing failure modes, their causes and effects using such MFMA tools as Process FMEA, Fault Tree Analysis. Establish effective countermeasures using MFMA tools such as P-Diagram and Fault Tree. Verify the effectiveness of the countermeasures in tests that include the effect of all key noise factors. Develop and validate Control Plans. Ensure alignment and synergy with the two other related KTP projects (e.g. the in-depth analysis conducted to identify appropriate process parameters to employ as the basis of Process Control Plans and Process capability improvement which are a key outcome from the Process Capability KTP will form the basis of countermeasure identification in the MFMA KTP.	**0.75**	P-FMEA Form Completed Control Plans for 5 axis CNC Machining Processes
Task 3.4	***MFMA Analysis of Sub-assembly Processes*** Apply the MFMA process to the sub-assembly process in order to identify potential manufacturing		

	failure modes and establish effective countermeasures using appropriate MFMA tools such as those identified in Tasks 3.3. Develop and validate Control Plans.	**0.75**	P-FMEA Form Completed Control Plans for Subassembly Processes
Task 3.5	***MFMA Analysis of control / inspection Processes*** Apply the MFMA process to the control / inspection process in order to establish the most appropriate roles for such facilities in support of a predictive process driven manufacturing engineering and production approach. Using appropriate MFMA tools identify potential failure modes in using the control / inspection process and establish effective countermeasures. Validate the effectiveness of the countermeasures through Production Validation. Develop and validate Control Plans.	**0.75**	P-FMEA Analysis / Form Completed Control Plans for Control / Inspection Processes Process performance tracking based on the Control Plans and MFMA KPIs
	(Stage total)	**(3.5)**	
Project Stage 4 – MFMA Process Implementation Phase 2: Carbon Composite Manufacturing			
Task 4.1	***Form Team + Roll out training*** Form MFMA roll-out team for *carbon composite complex machining* (CCM) area and agree roles and responsibilities. Conduct training as an integral part of team workshop/ application meetings in which Tasks 4.2 to 4.5 are completed	**0.25**	Training matrix
Task 4.2	***Identify Key Product and Manufacturing Process Characteristics*** Carry out a high level analysis using appropriate MFMA tools e.g. interface matrix analysis, to identify key product and process characteristics. Identification of key product characteristics will be based on information supplied by the product designers. Key manufacturing characteristics will be based on the high-level cascade of characteristics through the pilot area manufacturing processes. The identification of key manufacturing characteristics will be facilitated by the use of appropriate MFMA tools e.g. characteristic matrix analysis.	**0.5**	Process Map Key product and manufacturing process characteristic matrix P-FMEA Analysis / Form Completed Control Plans for ICY Machining Processes
Task 4.3	***MFMA Analysis of Carbon Composite (ICY) Machining Processes*** Apply the MFMA process to the carbon composite manufacturing and machining stages in order to identify potential manufacturing failure modes and establish effective countermeasures. Develop pre-launch and on-going Production Control Plans.	**0.75**	P-FMEA Form Completed Control Plans for Subassembly Processes
Task 4.4	***MFMA Analysis of Sub-assembly Processes*** Apply the MFMA process to the sub-assembly process in order to identify potential manufacturing failure modes and establish effective countermeasures. Develop pre-launch and on-going Production Control Plans.	**0.75**	P-FMEA Form Completed Control Plans for Control / Inspection Processes
Task 4.5	***MFMA Analysis of Control I inspection Processes*** Apply the MFMA process to the control / inspection		

	process in order to identify potential manufacturing failure modes and establish effective countermeasures. Validate the effectiveness of the countermeasures through Production Validation. Develop pre-launch and on-going Production Control Plans.	**0.75**	Process performance tracking based on the Control Plans and MFMA KPIs
Task 4.6	***Review of MFMA Process and Pilot Implementation*** Carryout a 'Lessons Learnt' teamwork exercise following the Pilot Implementation, involving all the members that participated in the Pilot. Review the MFMA process, the effectiveness of each tool applied as well as the process as a whole and the effectiveness of teamwork. Evaluate the impact on the key MFMA KPIs. Revise (fine tune) the MFMA process as required prior to subsequent implementation. Document and report on Lessons Learnt.	**0.5**	Lessons Learnt Report
	(Stage total)	**(4)**	
Project Stage 5 – Validation of impact of MFMA Process Implementation			
Task 5.1	***Validate the effectiveness of the MFMA process***: Check if new failure modes have been discovered after the application of the MFMA for the manufacturing processes in the pilot area, and investigate the reasons why these have not been captured by the MFMA. Working in conjunction with the Process Capability KTP project collect and collate Process Control information for the key process operations where process control improvement has been implemented in the pilot areas (see Tasks 3.5 and 4.5). Compare this data with the levels of Process Control (or the appropriate equivalent measures) achieved prior to the pilot implementation of the MFMA process. Document the level of variation in the key product characteristics associated with these key process operations. Summarise this variation the form of Process Capability indices (see Tasks 3.5 and 4.5). Compare this data with the levels of Process Capability (or the appropriate equivalent measures) achieved prior to the pilot implementation of the MFMA process. Prepare a report documenting the observed impact of the MFMA process based on process control and process capability indicators in the Pilot area.	**1**	Report on the impact of MFMA on process control and process capability in the Pilot Area.
Task 5.2	***Evaluate the effect of the MFMA process on the development of a Failure Avoidance culture in the Pilot Manufacturing area*** Conduct a survey of the teams directly involved in the MFMA implementation as well as the wider manufacturing personnel in the pilot area to evaluate the impact of the MFMA process implementation. The survey should aim to gauge the team's perception of the MFMA process itself (in terms of process steps,		

	teamwork and facilitation), and also the impact MFMA implementation has made towards a process based failure avoidance culture in the pilot area. Prepare a report based on analysis and discussion of the survey outcomes.	 **1**	MFMA Survey questionnaire issued; MFMA Survey Report to the Company
Task 5.3	***Validate the MFMA software support and reporting format*** Evaluate the effectiveness of the MFMA software support, making recommendations for further development if necessary (e.g. development of a integrated software package). Evaluate the effectiveness of the MFMA reporting format, focusing in particular on the communication interface with design and manufacturing engineering functions, and also with the supplier base.	 **0.25**	 Report on MFMA software effectiveness including recommendations for future development.
Task 5.4	***Cost / benefit analysis:*** Work with the Manufacturing Quality Assurance to review and update as necessary (on the basis of MFMA process mapping for the pilot area) the Company's Cost of Quality appraisal process, and on this basis evaluate the benefit of the MFMA process implementation. Alternative approach to cost / benefit analysis of failure mode avoidance can be based on the data used in Task 5.1 for different (selected) levels of success in avoiding failures 'up front'. ***(Stage total)***	 **0.75** **(3.0)**	 Cost of Quality Appraisal. MFMA Cost-benefit analysis.
Project Stage 6 – Process Analysis, Review & Documentation of Manufacturing Practice			
Task 6.1	***Evaluate the achievements of the MFMA implementation*** Review the outcomes of project stages 3, 4 and 5 and the detail of the pilot MFMA process by which these deliverables have been achieved. Compare MFMA deliverables such as the Control Plans with those used historically and draw conclusions relating to opportunities for improvement. Compare key production performance indicators for the MFMA pilot processes such as parts out of tolerance, tolerance waivers, amount of scrap and rework time with those obtained historically.	 0.25	 MFMA Implementation Report
Task 6.2	***Update the MFMA process as required and document a generic MFMA process.*** Based on the analysis conducted as a part of Task 6.1 update as required the MFMA process used in the pilot. Develop and document a generic MFMA process that could be implemented in the Company on processes similar to the MFMA pilot areas. Review the generic MFMA process with the Company.	 0.75	 MFMA Manual including generic MFMA analysis for typical processes.
Task 6.3	***Develop generic MFMA process for other manufacturing processes within the Company*** Synthesise families of similar parts and review the		

	manufacturing processes by which these families of parts are produced. Develop generic (high level) MFMA for each process. Establish a standard MFMA process for implementation across other CNC machining and carbon composite manufacturing facilities. Assess the applicability of the MFMA process to other manufacturing processes within the Company and supplier base.	0.25	Approved MFMA process / procedure
Task 6.4	***Document and Agree Standard Company MFMA Process*** Document the standard MFMA process developed as a part of Task 5.3. Review and agree the process with the Company.	0.25	***Decision point 3***: Agree the detail of the MFMA Process for standard procedure
	(Stage total)	***(1.5)***	
Project Stage 7 – Lessons learnt, dissemination and update Company processes			
Task 7.1	***Update Manufacturing Handbook to include Standard MFMA process*** Update the Manufacturing Handbook to include the Standard MFMA process developed as a part of task 5.4	0.25	Updated Manufacturing Handbook
Task 7.2	***Develop & roll-out Training.*** Develop training materials to support the roll-out of the Standard MFMA process across the Company. Develop and agree with the Company a roll-out strategy and schedule for the Standard MFMA process.	0.5	Training schedule and materials (see Task 2.5)
Task 7.3	***Project review*** Work with the Company and University supervisors to review the whole project. Review the management aspects of the KTP, time planning, and cost management. Present project review in a Company seminar.	0.25	Review report and Company seminar.
	(Stage total)	***(1)***	
TOTAL	Sum of total effort in months	**24**	

E. MFMA Handbook Extracts

Knowledge
Transfer
Partnerships

Section

A

A. EXECUTIVE SUMMARY

This document describes the Manufacturing Failure Mode Avoidance (MFMA) framework as a structured and pragmatic function-based approach to improve the robustness of manufacturing processes through the systematic identification of potential process failure modes and development of robust countermeasures and control plans. The framework is based on a coherent flow of information between proven process analysis tools, documented centrally in a Process Failure Modes and Effects Analysis (Process FMEA) form.

The MFMA process and tools support the effective management of the analysis through a structured function based decomposition of the process, which define the level of resolution of the analysis and the scope of responsibility of the team. Specific tools are introduced to support the systematic analysis of the process interfaces, both within the process boundaries (i.e. between the operations) and externally – with the environment and other processes / systems, with the aim of identifying sources of variation that can lead to failure modes and error states. The Process Flow Diagram and Critical Characteristics Matrix are introduced as key tools to document the functional relationships within the process including the effect of variability. The analysis in the Process FMEA further enhances this knowledge and information through criticality analysis, by identifying process failure modes associated with identified functions, their effects, and potential root causes associated with process parameters and interfaces characteristics. This directs process improvement actions (countermeasures to process failure modes) and the development of a robust process control plan. The Process FMEA is updated with robustness countermeasures and results from control plans implementation, serving, together with the associated MFMA document, as a definitive repository of process knowledge.

This document is intended as a handbook for the MFMA process deployment. A flowchart of the whole process is presented, followed by a detailed description and guidelines for each of the supporting tools, illustrated with an example from a MFMA process deployment to a case study at Further case studies of MFMA deployment at structured as technical reports, are included in the Appendix.

1

Section B

B. THE PROGRAMME

B.5.4.7 Characteristic Matrix

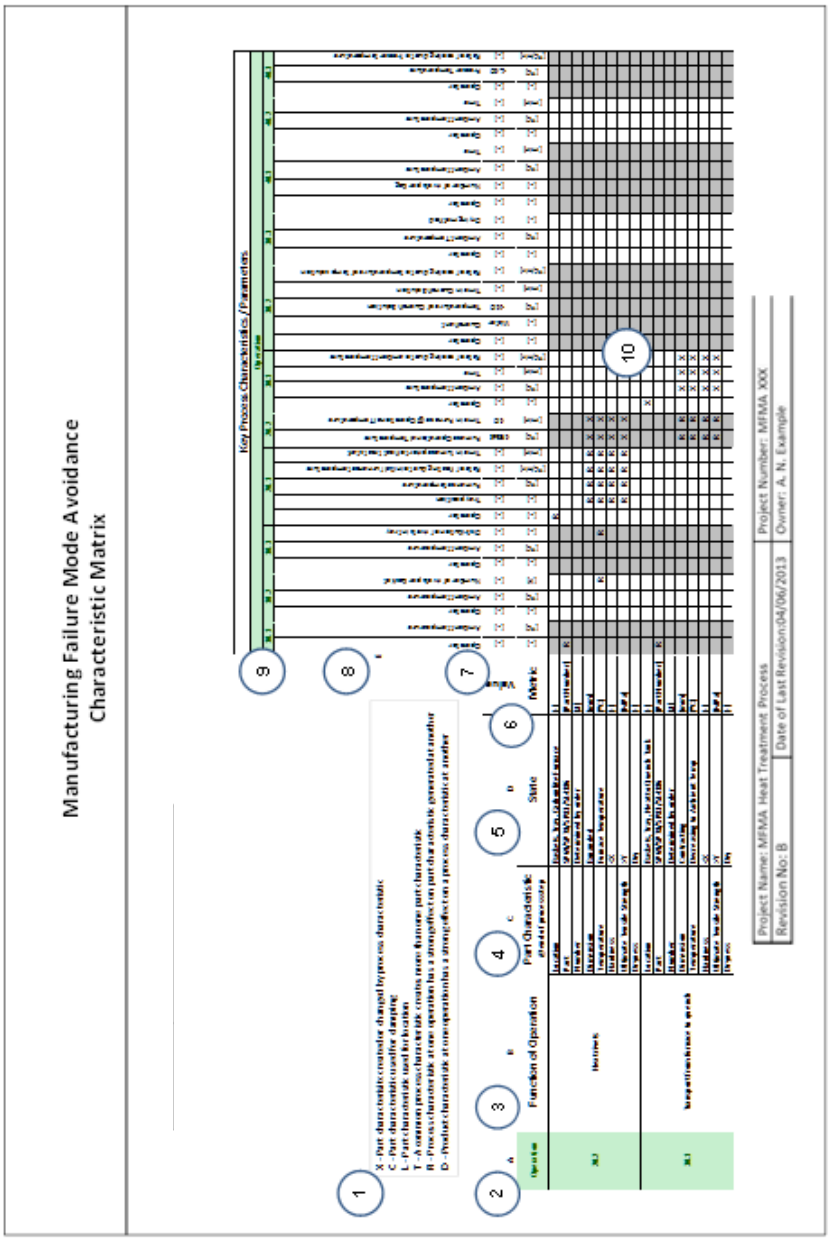

Figure 24: MFMA Characteristic Matrix Worked Example

B.5.4.7.1 Tool Objective

The Characteristic Matrix is used to identify and characterise the nature of the relationships between the part and process characteristics throughout the entire process. By listing the characteristics of the part on the vertical axis and the characteristics of the process on the horizontal axis, all relationships can be systematically and independently considered, which facilitates a comprehensive understanding of the process, by documenting specifically how and when characteristics influence each other throughout the entire manufacturing process. The information contained in the Characteristic Matrix provides a strong foundation for the identification of potential failure modes as it highlights dependencies between the parts and process, which aids in identifying the effects, or causes, of process failures on subsequent, or respectively preceding, operations. The Characteristic Matrix also defines the scope of the Process FMEA, as defined in the Boundary Diagram and Process Maps and preserved through the MFMA study.

B.5.4.7.2 Required Resource

In order to begin the Characteristic Matrix, the Process Flow Diagram must be completed so that all of the part and process characteristics are known. As with the Process Flow Diagram, there is a strong flow on information into this tool, allowing the Facilitator to efficiently compile the axes. A series of meetings will be required between the Facilitator, Team Leader and Team members to analyse the relationships between part and process characteristics at each operation.

B.5.4.7.3 Tool Components

1. **Key** – This explains the different symbols used to denote the nature of the relationships between the process and part characteristics. The key provided is purely an example, different characters and relationships can be added or removed as appropriate to the process that is being studied.

2. **Operation** – The identification number of the process operation. These are defined within the Process Maps.

3. **Function of Operation** - Directly inputted from the Process Maps.

4. **Part Characteristic** – The characteristics of the part that are defined on the Boundary Diagram.

5. **Part State** – These are inputted from the part states described in the Process Maps.

6. **Metric** – The metric that is used to measure the process and part characteristics

7. **Value** – The intended value of the process and part characteristics

8. **Operation** – The operations in which the process characteristics are applied

9. **Process Characteristic** –The process inputs that are used to create, alter or influence the part characteristics

10. **Matrix** – The symbols are inputted to highlight a relationship, intended or otherwise, between the part and process characteristics